THE JOURNAL OF GEOLOGY

VOLUME 60 SEPTEMBER 1952 NUMBER 5

FABRIC OF QUARTZITES NEAR THRUST FAULTS . . . . . Robert Balk 415

PHASE RELATIONS OF THE ALKALI FELDSPARS. I. INTRODUCTORY REMARKS
Fritz Laves 436

SELENOMORPHOLOGY . . . . . Alice Coleman 451

ORIGIN OF THE MIMA MOUNDS, THURSTON COUNTY REGION, WASHINGTON
R. C. Newcomb 461

SUBMARINE "NATURAL LEVEES" . . . . . Edwin C. Buffington 473

A HIGH-LEVEL BOULDER DEPOSIT EAST OF THE LARAMIE RANGE, WYOMING
J Harlen Bretz and Leland Horberg 480

GEOLOGICAL NOTES

Improved Equipment and Techniques for Orientation Studies of Large Particles in Sediments . . . . . Thor N. V. Karlstrom 489

REVIEWS 494

ERRATUM 509

PUBLICATIONS RECEIVED 510

THE UNIVERSITY OF CHICAGO PRESS • CHICAGO

September 1952 Vol. 60, No. 5

THE JOURNAL OF GEOLOGY

F. J. PETTIJOHN, Editor JEAN G. SIMMONS, Assistant Editor

CONTRIBUTING EDITORS

ROBERT BALK, University of Chicago
T. F. W. BARTH, Universitetet i Oslo
N. L. BOWEN, Geophysical Laboratory
C. W. CORRENS, Universität Göttingen
D. J. FISHER, University of Chicago
LELAND HORBERG, University of Chicago
PH. H. KUENEN, Geologisch Instituut, Groningen
W. H. NEWHOUSE, University of Chicago
E. C. OLSON, University of Chicago
KALERVO RANKAMA, Helsingin yliopisto
N. A. RILEY, California Research Corporation
MARCEL ROUBAULT, Université de Nancy
R. P. SHARP, California Institute of Technology
J. M. WELLER, University of Chicago
F. E. WICKMAN, Riksmuseet, Stockholm

The Journal of Geology is published bimonthly in January, March, May, July, September, and November by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago 37, Illinois. ¶ Subscriptions are by volume only. The subscription price is $7.00 per volume, the price of single copies is $1.50. Orders for service of less than a full volume will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States and its possessions. No extra charge for countries in the Pan American Postal Union. ¶ Postage is charged extra as follows: for Canada and Newfoundland, 40 cents per volume (total $7.40), 10 cents per issue (total $1.60); for all other countries in the Postal Union 75 cents per volume (total $7.75), 15 cents per issue (total $1.65). ¶ Subscriptions are payable in advance. Please make all remittances payable to The University of Chicago Press in United States currency or its equivalent by postal or express money orders or bank drafts.

The following is an authorized agent:

For the British Empire, except North America and Australasia: Cambridge University Press, Bentley House, 200 Euston Road, London, N.W. 1, England. Prices of yearly subscriptions and of single copies may be had on application.

Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit.

Business correspondence should be addressed to The University of Chicago Press, Chicago 37, Ill.

Communications for the editors and manuscripts should be addressed to the Editor of THE JOURNAL OF GEOLOGY, Rosenwald Hall, The University of Chicago, Chicago 37, Ill.

The articles in this Journal are indexed in the *International Index to Periodicals*, New York, N.Y.

Applications for permission to quote from this Journal should be addressed to The University of Chicago Press, and will be freely granted.

Microfilms of the Journal are now available to regular subscribers only and may be obtained at the end of the volume year. Inquiries concerning purchase should be addressed to University Microfilms, 313 North First Street, Ann Arbor, Michigan.

Notice to subscribers: If you change your address, please notify us and your local postmaster immediately.

Entered as second-class matter February 29, 1944, at the post office at Chicago, Ill., under the Act of March 3, 1879.
Acceptance for mailing at special rate of postage provided for in United States Postal Act of October 3, 1917, Section 1103, amended February 28, 1925, authorized July 15, 1918.

[PRINTED IN U.S.A.]

AMONG the papers to appear in early issues of the *Journal* are the following:

"Submarine Geology off San Diego, California." By K. O. EMERY, W. S. BUTCHER, W. S. GOULD, and F. P. SHEPARD

"Phase Relations of the Alkali Feldspars. 2. The Stable and Pseudo-stable Phase Relations in the Alkali Feldspar System." By FRITZ LAVES

"Late Cenozoic Marine Glacial Sediments and Marine Terraces of Middleton Island, Alaska." By DON J. MILLER

"Chemical Composition of Pre-Cambrian Slates, with Notes on the Geochemical Evolution of Lutites." By R. H. NANZ, JR.

"Virgilian Reefs of the Sacramento Mountains, New Mexico." By WILLIAM J. PLUMLEY and ROY W. GRAVES, JR.

"The Erosional Origin of the Mima Mounds of Southwestern Washington." By ARTHUR M. RITCHIE

"The Camouflage Principle and Trace-Element Distribution in Magmatic Minerals." By DENIS M. SHAW

"Pleistocene Evolution of the Ohio and Wabash Valleys." By WILLIAM J. WAYNE

"Periglacial Frost-Thaw Basins in New Jersey." By PETER E. WOLFE

"The 10 Per Cent $CaAl_2Si_2O_8$ Plane in the System $CaSiO_3$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$-$CaAl_2Si_2O_8$." By HATTEN S. YODER, JR.

SUGGESTIONS TO CONTRIBUTORS

TEXT—Manuscripts must represent original work and must not have been published elsewhere. They should be written in English, or in French or German with an adequate summary in English. They should be original copies, typewritten, on one side of paper only, double spaced, and with wide margins. References and footnotes should also be double spaced.

ABSTRACT—Each major article should contain an abstract which gives a concise summary of the content, including both major and minor points. Abstracts should not exceed 200 words.

REFERENCES—Under the heading "References Cited" at the end of the paper should be listed all literature cited, arranged alphabetically by authors and chronologically under each author, using the following form:

DOE, J. S. (1884*a*) Geology of the Big Ben Mountains: U.S. Geol. Survey Prof. Paper 55.

——— (1884*b*) Petrography of the granites, New York, Macmillan Co.

SMITH, A. V. (1926) Discovery of fish remains in Ordovician rocks of the Black Hills (abstr.): Geol. Soc. America Bull. 52, p. 27.

——— and DUNSANY, A. J. (1929*a*) Early Ordovician faunas of South Dakota: U.S. Geol. Survey Bull. 444, pp. 1–76.

——— ——— ——— (1929*b*) Revision of Ordovician stratigraphy of the Black Hills: Jour. Geology, vol. 37, pp. 680–695.

In the text, references to the literature cited should follow this form: (Smith, 1928, p. 36).

FOOTNOTES—Discussion which has a collateral bearing on the subject being discussed but would be too much of an interruption to be put in the body of the text should be inserted as a footnote. Footnotes should be typed all together on a separate page and numbered consecutively.

ABBREVIATIONS—This *Journal* uses the abbreviations approved by the United States Geological Survey and listed in the Survey's *Suggestions to Authors*.

ILLUSTRATIONS—Maps, line drawings, and diagrams should be prepared on white drawing paper or on tracing cloth, with India ink. Care should be taken not to overload maps with irrelevant detail or, at the other extreme, to use excessive amounts of space to convey relatively little information. The smallest symbols or letters used should be of such size that they will be not *less* than 1 mm. high after reduction. Unsatisfactory illustrations will be returned to the author or may, with his permission, be redrafted at the editorial office at his expense.

Photographs are reproduced by the collotype process. Authors should use the minimum number consistent with adequate presentation of the subject. If a paper includes a disproportionately large number of plates, the editor may ask the author to pay a portion of the cost of illustrations. Photographs should be sharp and clear, printed on glossy paper, and either of the size in which they are to appear in the *Journal* or larger.

Explanations of all figures should be typed on one or more separate sheets. Each figure should be marked for identification and top indicated if there is any doubt.

The original illustrations are destroyed following their publication, unless the author has requested their return in advance of publication.

ALTERATIONS—The cost of alterations (i.e., changes from the original manuscript) made by the author, exceeding 5 per cent of the cost of setting the article in type, will be charged to him. No changes should be made in proof except errors of typography.

REPRINTS—The *Journal* supplies free 25 reprints (without covers) of each major article. This does not include geological notes, discussions, reviews, or communications to the editor. Additional reprints may be ordered when manuscript is submitted or at any time in advance of publication. Rates will be furnished on request.

STYLE—In matters of style, spelling, abbreviation, etc., the two guides to be followed are the University of Chicago Press *Manual of Style* and the United States Department of the Interior *Suggestions to Authors*. Where these authorities differ, the latter reference is to be used.

VOLUME 60 NUMBER 5

THE JOURNAL OF GEOLOGY

September 1952

FABRIC OF QUARTZITES NEAR THRUST FAULTS[1]

ROBERT BALK
University of Chicago

ABSTRACT

Near east-dipping thrust faults in the Green Mountains and Berkshire Hills, New England, quartzites exhibit westward overturned folds with subhorizontal axes, and an axial-plane cleavage dips east. Close to a thrust fault the cleavage becomes so intense that it obscures the limbs of folds. Where the quartzite has been folded isoclinally, the cleavage is essentially parallel to the limbs but cuts across apices of folds.

Intersections of gently folded beds and axial plane cleavage produce a *b*-lineation that coincides with the orientation of the fold axes. Close to thrust faults, however, an *a*-lineation becomes more prominent. On the eastward-dipping *s*-planes, the *a*-lineation agrees closely with the dip of the planes, although in places its bearing deviates slightly to the east-southeast. Folds with axes parallel to this *a*-lineation are rare and small.

In mildly deformed quartzite, several hundred feet from thrust faults, quartz grains are slightly elongated parallel to the *b*-fabric axis, and the *c*-axes of the grains show one strong orientation maximum in a north-northeasterly direction, closely aligning themselves with the fold axes. Near thrust contacts, however, a *bc*-girdle of *c*-axes develops that retains a maximum close to *b*, although additional maxima may form. Deformation lamellae are virtually lacking, but planes of liquid inclusions are locally prominent and follow *ac*-planes.

Even a few feet from thrust contacts, quartz grains remain slightly elongated parallel to *b*, but the megascopic *a*-lineation is marked by numerous discontinuous tracts of equant grains of feldspar, muscovite, tourmaline, and zircon. The quartz grains in these tracts differ in orientation from the surrounding quartz fabric. This textural feature has close analogies in rolled steel and glass. In conjunction with *bc*-girdles and a megascopic *a*-lineation, it may prove to be a useful criterion for the identification of rock fabric developed by thrusting.

INTRODUCTION

For some time the writer has been interested in structural problems of the Taconic Range in eastern New York—a range believed by some to be the remnant of a large thrust sheet; one author has assumed that the rocks have been moved nearly 70 miles to their present resting place. Unfortunately, exposures at critical localities are poor or lacking, and, in order to arrive at a more reliable picture of the structural history of the range, it became desirable to examine the nature of certain criteria that may be used to decide whether formations are in thrust contact or not. That such criteria are needed has been pointed out by E. B. Knopf (1935).

Some rock fabrics were therefore investigated close to exposed thrust faults, and one of the most rewarding rocks proved to be the Lower Cambrian Cheshire quartzite, exposed along the west flanks of the Green Mountains and the Berkshire Hills in western New England, accompanying the Taconic Range a few miles to the east (fig. 1). In recent years several authors have described quartz fabrics near thrust faults in Scandinavia and Scotland, and those examined in the Berkshire Hills appear to be very similar to the European ones. The present study was, however, essentially a by-product

[1] Manuscript received October 2, 1951.

of an areal structure study. It was undertaken to see whether megascopic and microscopic fabrics are related in a reliable way. During the study, new problems arose, the investigation of which would necessitate additional material; but, as we are unable to revisit the area in the near future, it seems best to publish the data now assembled, even though, of necessity, the results are somewhat qualitative and the conclusions tentative.

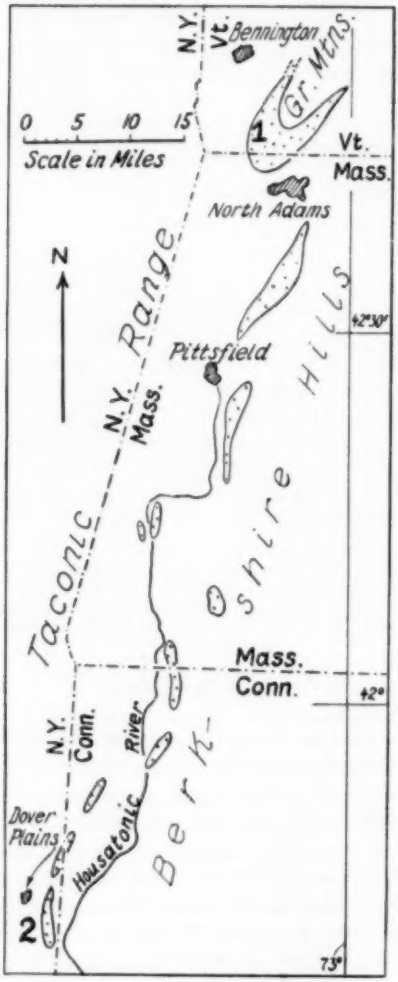


FIG. 1.—Outline map of quartzite belt on west flank of the Berkshire Hills, Green Mountains, New England. Stippling shows general location of quartzite outcrops based on state maps of New York, Connecticut, and Massachusetts and on the Geological Map of the United States (1933), as well as on private observations. The numbers *1* and *2* refer to special areas shown in fig. 2.

GEOLOGIC SETTING OF GREEN MOUNTAINS–BERKSHIRE HILLS THRUST ZONE

The Green Mountains of southern Vermont, as well as their southern continuation in Massachusetts and Connecticut known as the Berkshire Hills, are composed of an uplifted core of pre-Cambrian gneisses and schists of various origins. On its west side the basement complex is overlain unconformably by a sequence of early Paleozoic formations that begins with the Lower Cambrian Cheshire quartzite, known also, in southeastern New York, as the Poughquag quartzite. Carbonate rocks of late Cambrian and Ordovician age, as well as late Ordovician argillaceous rocks that lie above the quartzite, are of no interest in connection with the present study.

Outcrops of the quartzite have been mapped by various workers along the west flank of the crystalline tract from the New York City district northward at least to the vicinity of Rutland, Vermont, a distance of more than 160 miles. The more important ones are shown in figure 1. Where the uplift has been broad and domelike, the quartzite has been tilted westward, as, for example, in places along the Hudson highlands of New York. Where a vertical fault borders the gneiss on the west side, the quartzite has commonly been flexed into a vertical attitude, as along the steep, west-facing scarp, 3 miles north-northeast of Lee, Massachusetts (7½′ East Lee,

Massachusetts, Quadrangle), and at many other places.

Commonly, however, the uplift has had a component directed obliquely upward to the west, and the deformation resulting from these upthrusts prompted the present study. Two districts were selected for special study. They are shown in figure 1. The southern one, in Dutchess County, New York, investigated some years ago (Balk, 1936), was restudied; the northern one, in the vicinity of a mountain known as the Dome (15′ Bennington, Vermont, Quadrangle) in southwestern Vermont, was mapped in 1926 and was revisited in 1949 and 1950. It would have been desirable to show in the outline map the fault system that borders the Berkshire Hills–Green Mountain tract on the west side, but mapping is of unequal quality in different sections, glacial deposits obscure much of the zone, and the degree of accuracy would be too variable. For that reason, we have confined ourselves to showing the two selected areas in greater detail in figure 2.

STRUCTURE OF QUARTZITE IN DUTCHESS COUNTY, NEW YORK

The general structure of the Cambrian quartzite in the Dutchess County area has been described in sufficient detail in a previous paper (Balk, 1936, pp. 732–736), so that only the salient points need be stated here. Where the pre-Cambrian basement has been disturbed by high-angle upthrusts of small displacement, the overlying quartzite, if brittle, was faulted into narrow, parallel, north-south–trending belts of slightly tilted blocks or, if micaceous interbeds rendered it more flexible, developed open folds with gently dipping limbs and subhorizontal axes trending north-south or north-northeast–south-southwest.

Where the horizontal component of the thrust movement was more appreciable, because of either greater displacement or gentler dip angle of a thrust fault, the quartzite folds are overturned to the west or west-northwest and may reach isoclinal cross sections, where thin, micaceous beds are abundant. East-dipping axial-plane slip cleavage, marked by films of muscovite and tourmaline, accompanies the folds and commonly displays small-scale shearing and thrusting of individual beds upward to the west. Intersection of the axial-plane slip cleavage and the limbs of folds produces a *b*-lineation, which is widespread in sections of mildly deformed quartzite.

Near a thrust fault, isoclinal westward-overturned folds become more numerous, and in places one can see recumbent folds with nearly horizontal limbs (Balk, 1936, pl. 12, fig. 1). In most outcrops, however, the eastward-dipping slip-cleavage planes are so pronounced that they have blurred the apices of folds, and, where the original beds were of uniform lithology and grain size, it may be impossible to distinguish megascopically the limbs of folds from the cleavage planes. Instead, one sees essentially one set of *s*-planes only, dipping eastward parallel to the dip of the nearest thrust. Dip angles vary widely but, in the author's experience, angles near 50° and 60° are most common.

That the pre-Cambrian thrust blocks have moved essentially up-dip from east to west can be inferred from the outcrop pattern of several thrust contacts, as well as from associated drag. Several thrusts have been described (Balk, 1936, pp. 734, 737–750).

As much as 2 miles west of a given thrust fault, the eastward-dipping *s*-planes exhibit a lineation that agrees closely with the dip of the planes, al-

though its bearing may deviate slightly from the dip direction of the *s*-planes. At all thrust contacts this lineation passes from Paleozoic into pre-Cambrian rocks and clearly marks the direction of thrust movement. According to accepted terminology (Fellows, 1943, pp. 1406–1409; Cloos, 1946, pp. 4–6; Fairbairn, 1949, p. 6) it is an *a*-lineation. Close to thrust contacts it may be so intense that *s*-planes are blurred by it, especially in the gneisses. Far west of a thrust fault the *a*-lineation fades out, and there are exposures where both *b*- and *a*-lineation can be seen. Essentially, the *a*-lineation may be regarded as the equivalent of

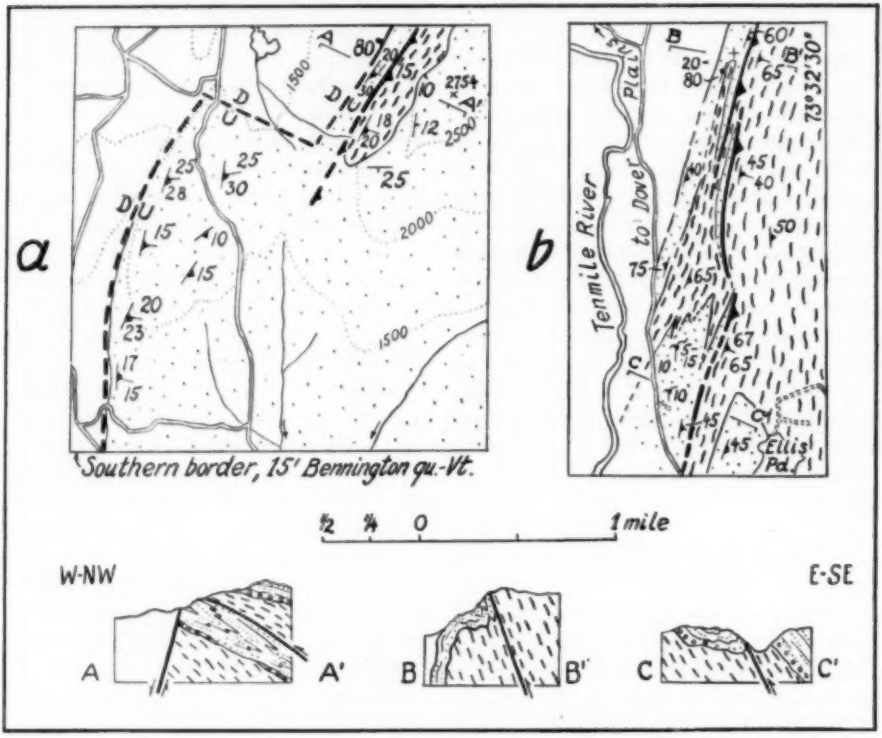


FIG. 2.—Structure maps and cross sections of two areas of thrust-faulted quartzite. *a*, Vicinity of the Dome, southwestern Vermont (15' Bennington Quadrangle). Cross with elevation figure *2754* shows top of Dome Mountain. Contour lines of 2,500, 2,000, and 1,500 feet; elevation, roads, and drainage copied from quadrangle map. *b*, Area east of Tenmile River and northwest of Ellis Pond, eastern New York (7½' Dover Plains Quadrangle).

Wavy dashes: pre-Cambrian, undifferentiated; *dots:* Lower Cambrian quartzite; *blank:* later sedimentary rocks. Basal beds of quartzite shown by open circles in cross sections. Heavy lines with dip angle: thrust faults. Faults with *D*/*U* are normal faults, *D* denotes dropped block. One-barbed arrow, in cross sections, shows relative movement of faults. Solid lines are well-exposed faults, rows of dashes show inferred course of fault. Lines *A*–*A'*, *B*–*B'*, and *C*–*C'* show position of cross sections. Strike and dip symbols without triangles: undeformed quartzite; cross: horizontal beds; triangles with figures: strike and dip of *s*-planes; lines starting from center of triangles show trend of lineation, figure gives plunge angle. Wavy strike and dip symbols show undulatory beds with trend and plunge angle of fold axes, northwest of Ellis Pond. Uniformly east-dipping slip cleavage is not shown.

slickensides along a fault, except that in the rocks here discussed the striations pervade a thickness of several hundred feet of rocks, whereas striations along a common fault are restricted to a rather thin plate of crushed rock.

Close to thrust faults there are a few folds with axes parallel to the *a*-lineation. Search for these folds in the Taconic Range and in the southern Green Mountains confirms our earlier experience in Dutchess County (Balk, 1936, p. 738) that folds of this orientation are small, with wave lengths measured in inches rather than in feet. Most of those seen are nearly isoclinal.

STRUCTURE OF QUARTZITE AT THE DOME, SOUTHWESTERN VERMONT

The summit of the Dome, south of Bennington, Vermont, and 75 miles north of Dutchess County, New York, is made up of a large plate of the quartzite that rests in essentially undisturbed condition upon the pre-Cambrian gneiss (fig. 2, *a*). Northwest of the summit and about 200 feet below it, the unconformity at the base of the quartzite is exposed.

Farther down on the northwest slope of the mountain, the pre-Cambrian gneiss is seen to be thrust northwestward, over the western continuation of the quartzite. This thrust can be mapped for about 1 mile, and, where the exposures are good, low dip angles, near 15°, are measured. Quartzite cliffs below the thrust display fine-grained pure quartzite, with arkosic as well as micaceous interbeds. Isoclinal folds strike north-northeast, but the axes of a few small ones plunge east-southeast under the gneiss, as does the intense *a*-lineation.

About $\frac{3}{4}$ mile southwest of the exposed thrust at the Dome, the quartzite forms a prominent west-facing scarp, terminated on the west by a system of normal faults that have dropped younger rocks to the level of the quartzite. The pronounced *a*-lineation in the rocks at the scarp leaves little doubt that the quartzite has been deformed along a thrust fault, but till conceals its trace. The quartzite plate could be *under* a concealed thrust east of the scarp or *above* a thrust concealed by the downfaulted younger rocks west of the scarp and talus at the west base of the scarp; it might even be a thrust sliver *between* thrusts. In the field the lower half of the section seemed to display the *a*-lineation more strongly than the top portion, but otherwise the structure of the rocks in both outcrop areas is identical. It was thought that a fabric examination might help to locate the concealed thrust fault.

SAMPLING PROCEDURE

The two selected areas are particularly advantageous for a fabric study because they exhibit undisturbed, mildly deformed, and intensely deformed quartzite in close proximity to one another. Thus it seems possible to trace something like an evolution of the fabric, just as the megascopic structural features can be correlated with the intensity of deformation.

Altogether, 63 oriented sections were prepared from 19 localities, and 43 fabric diagrams were made. Rocks other than quartzite were also sampled, and work on these is in progress. In each thin section, 300 quartz grains were plotted, and the contours mark the 1, 3, 5, 10, and 20 per cent lines, unless the legend specifies other figures. In this way the diagrams can be compared at a glance. Each fabric diagram shows the strike and dip of the surface represented by the thin section by means of the customary strike and dip symbol. The author follows the system used by E. Cloos and A. Hietanen

(1941) and explained by Gair (1950, p. 869). In figure 50, for example, the surface that dips steeply to the left has on the left side of the strike bar a *5*, and on the right side a *185*, which means that on the reader's left side is the direction N. 5° E., and on his right side the direction N. 185° E., so that he is looking at the surface of the thin section in the direction N. 95° E. The dip figure, *70°*, means that the thin-section surface dips toward the reader at 70°. If the dip is away from the reader, this figure is given by the total angle, starting in the quadrant that faces the reader. For example, if a thin-section surface dips at 70°, but away from the reader, the dip figure would be 110°. With a few exceptions, dips in the diagrams in this paper do not exceed 90°.

UNDEFORMED QUARTZITE

The only specimen of undeformed quartzite was collected about 4 feet above the unconformity with the pre-Cambrian gneiss, northwest of the summit of the Dome. Megascopically, it shows numerous quartz pebbles, 1–6 mm. across, and fewer of feldspar. Layers near by display conglomeratic lenses with pebbles of granitic composition as much as 1 inch in diameter. Scales of muscovite impart a greenish hue to the lowermost beds.

The microscope shows a groundmass of quartz grains, about $\frac{1}{15}$ mm. in diameter, with somewhat larger grains of magnetite, zircon, tourmaline, and some pyrite. Potash feldspar and some plagioclase are present as large fragments, and a considerable number of the clastic quartz fragments exhibit strain shadows which they must have acquired in pre-Cambrian time, for they are surrounded by relaxed, strain-free groundmass quartz. Muscovite, in well-recrystallized plates, makes up about 10 per cent of the rock. Quartzite ledges at the Dome are traversed here and there by quartz-feldspar veins too fine-grained to deserve the name "pegmatite" but capable of producing microcline, muscovite, biotite, tourmaline, and apatite. The quartzite is believed to have acquired its present makeup under conditions of low-grade metamorphism.

Although the rock lacks any signs of megascopic deformation, the microscope shows that some of the smaller clastic fragments have been flattened and broken down along their margins, giving rise to little clusters of quartz grains in similar crystallographic orientation. This makes interpretation of the quartz fabric difficult, for it is impossible to decide whether the mosaics of similarly oriented small grains represent the margin of a larger clastic grain, which, itself, lay above or below the thin-section surface, or a group of groundmass quartz grains in which some resorption of the small ones by larger ones had begun, owing to recrystallization. Larger clastic fragments, at any rate, were not measured. Two diagrams (figs. 4 and 5), one parallel, the other at right angles to the bedding, show what had been expected: low concentrations of *c*-axes, and in diverging directions. In view of the advanced recrystallization, it may prove very difficult, if not impossible, to ascertain whether this rock possessed a diagnostic primary quartz orientation or preferred grain shape (Rowland, 1946).

MILDLY DEFORMED QUARTZITE

Mildly deformed quartzite was examined at a locality east of Tenmile River and northwest of Ellis Pond ($7\frac{1}{2}'$ Dover Plains Quadrangle, New York, Connecticut; fig. *2*, *b*, cross section *B*–*B'* and

C–C'; fig. 3). The locality east of Tenmile River is one of the most interesting ones in the Dutchess County quartzite area, because here are preserved all stages of deformation of the quartzite within a few hundred feet of one another. Between a thrust fault on the east and a vertically tilted section on the west, a flat plate of quartzite rests astride a narrow block of pre-Cambrian gneiss, still preserving the original unconformity at the base. Though it exhibits slight undulations of the beds and axial-plane slip cleavage in micaceous interbeds, this strip of quartzite has certainly not been deformed so intensely as the western and eastern terminations of this mass. Similarly, northwest of Ellis Pond, about 500 feet west of a thrust fault, a narrow erosion remnant of the quartzite retains nearly horizontal bedding. Axial-plane cleavage is hard to see in quartzose beds but can be observed dipping east at high angles. Its intersection with the subhorizontal fold axes produces an elusive *b*-lineation trending north-northeast.

Three specimens were taken from the Tenmile River locality, the westernmost one at an elevation of 4 feet above the unconformity; the second about 12 feet above the pre-Cambrian floor and about 120 feet east of the first one; and the third about the same elevation above the unconformity and 45 feet east of the second specimen. The orientation of the thin-section surfaces is shown diagrammatically in figure 3.

In contrast with the undisturbed quartzite, the fabric diagrams prepared from the three Tenmile River specimens (figs. 6–12) show pronounced fabric maxima (17 per cent in the first specimen, 12 per cent in the second, 16 per cent in the third). Two of them trend north-south but have a gentle southerly plunge, whereas the megascopic *b*-lineation plunges slightly to the north. In the third specimen (figs. 10–12) a strong maximum plunges obliquely northeast, as do the local fo' ' axes. It may be remarked here that divergences of significant orientations up to 20° are expectable. It is impossible to measure the

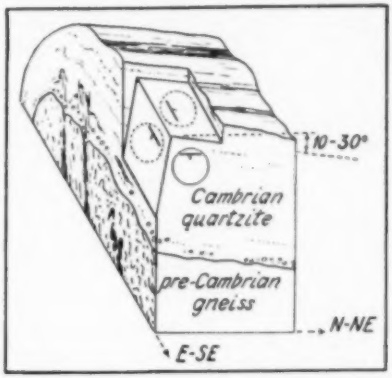


FIG. 3.—Block diagram to show detailed structure of cross-section *B–B'* east of Tenmile River (fig. 2). Basal quartzite beds rest nearly horizontally above pre-Cambrian gneiss. Unconformity exposed at west end of 400-foot section. Eastward the quartzite is terminated by the thrust fault shown in cross-section *B–B'*. An exposed quartzite section preserves bedding in open folds and shows axial-plane cleavage in micaceous beds. Orientation of thin sections obtained in this zone is shown by cut-out block.

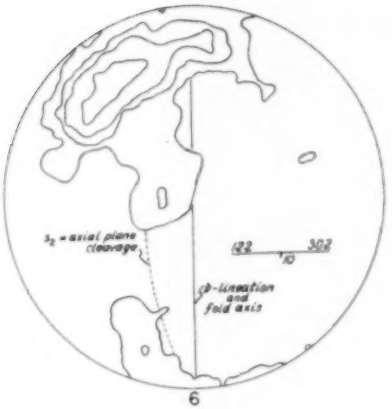
orientation of the *b*-lineation or fold axes with greater accuracy than about 5°–10°. Even in the same block the directions may vary that much. The same is true for the strike and dip of slip cleavage. On large surfaces one may obtain a good average, but on the smaller, sawed surface of a hand specimen the angles may vary. On the still smaller scale of a thin section, the poles of micas may again indicate one or two planes whose orientation differs from the megascopic *s*-plane by several degrees. Tuttle (1949, p. 346) and Cloos and Hietanen (1941, p.

FIGS. 4–46.—Fabric diagrams of quartzite from Dutchess County, New York, and vicinity of the Dome, southwestern Vermont. Each diagram shows *c*-axis orientation of 300 quartz grains. Unless otherwise specified in legend, the contours are 1, 3, 5, 10, and 20 per cent.

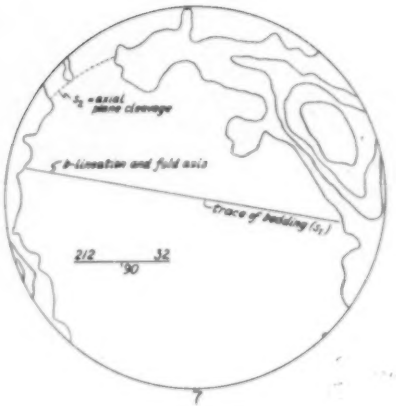
Figure	Location	Description
4	NW. slope of Dome, 15′ Bennington Quad., Vt., 4 ft. above unconformity	Undisturbed; groundmass grains for most part. Section ‖ bedding
5	Same as 4	Section across bedding
6	W. end of outcrops, E. of Tenmile River, 7½′ Dover Plains Quad., N.Y., Conn., 4 ft. above unconformity	Section ‖ bedding; maximum at 13 per cent
7	Same as 6	Section across bedding; maximum at 17 per cent
8	Same as 6, 12 ft. above basal unconformity	Section ‖ bedding; maximum at 12 per cent
9	Same as 8	Section ⊥ bedding; maximum at 11 per cent
10	Same as 8, about 45 ft. to E.	Section ‖ bedding; maximum at 11 per cent
11	Same as 10	Section vertical, ‖ fold axis; maximum at 13 per cent
12	Same as 10	Section ⊥ fold axis; maximum at 16 per cent. Trace of bedding not shown, as it is somewhat folded; it would approximate a gentle arch across the diagram from left to right
13	Crest of gentle anticline, about 500 ft. W. of thrust fault, NW. of Ellis Pond, Dover Plains Quad.	Section ‖ bedding; maximum at 20 per cent
14	Same as 13	Section across bedding and fold axis; maximum at 23 per cent
15	E. of Tenmile River, 9 ft. below thrust fault	Quartzite with *a*-lineation. Section ‖ E.-dipping *s*-planes; suggestion of incomplete *bc*-girdle; maximum at 25 per cent
16	Same as 15	Section across *s*-planes and *a*-lineation; incomplete *bc*-girdle; maximum at 17 per cent
17	Same as 15, about 4 ft. below thrust fault	Section ‖ *s*-planes; incomplete *bc*-girdle; maximum at 17 per cent
18	Same as 17	Section across *s*-planes and *a*-lineation; incomplete *bc*-girdle; maximum at 15 per cent
19	Same as 17	Section across *s*-planes, ‖ *a*-lineation; incomplete girdle, dips 20° gentler than *bc*-plane; maximum at 20 per cent
20	NW. of Ellis Pond, about 30 ft. below thrust fault	Section across *s*-planes and *a*-lineation; 1, 3, 6, and 10 per cent contours; incomplete *bc*-girdle, 30° flatter than theoretical *bc*-plane; maximum at 14 per cent
21	Same as 20	E.–W. section across *s*-planes, ‖ *a*-lineation; nearly complete girdle, dips about 35° flatter than theoretical *bc*-plane; maximum at 12 per cent
22	NW. slope of the Dome, SW. Vermont, about 60 ft. below thrust fault	Section across *s*-planes and *a*-lineation; incomplete *bc*-girdle; maximum at 8 per cent
23	Same as 22	Section across *s*-planes, ‖ *a*-lineation; nature of girdle uncertain; maximum of 10 per cent ‖ *b*
24	Same as 22, about 45 feet below thrust fault	Arkose layer; incomplete *bc*-girdle; maximum at 12 per cent
25	W.-facing scarp, about ¾ mi. SW. of Dome, easternmost, structurally highest, layers	Quartzite with *a*-lineation; section ‖ E.-dipping *s*-planes; incomplete girdle, 20° steeper than *bc*-plane; maximum at 11 per cent
26	Same as 25	Section across *s*-planes, ‖ *a*-lineation; incomplete girdle, 30° steeper than *bc*-plane; maximum at 17 per cent
27	Same as 25	Section across *s*-planes and *a*-lineation; girdle 15° steeper than *bc*-plane; maximum at 10 per cent

4

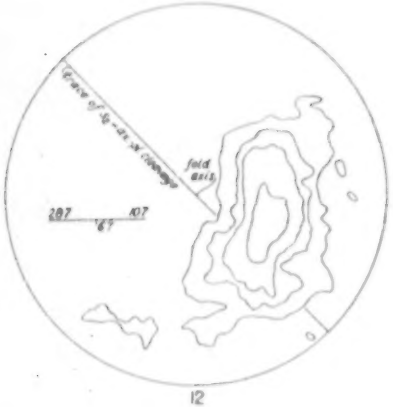
5



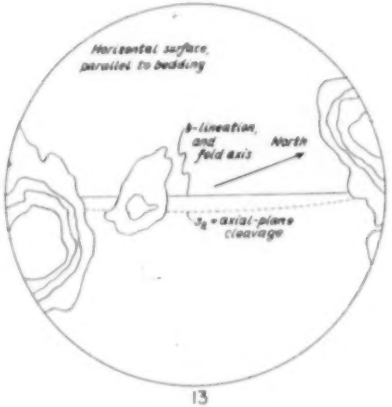
6



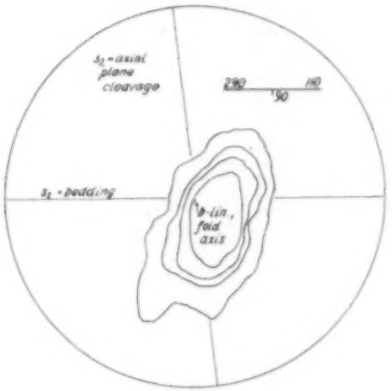
7



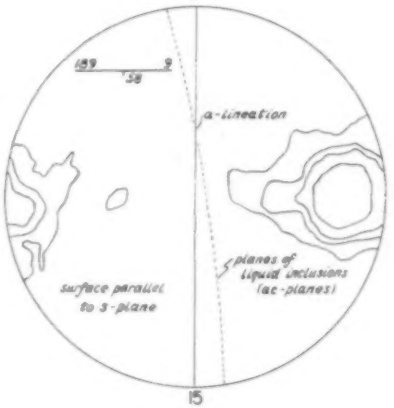
12



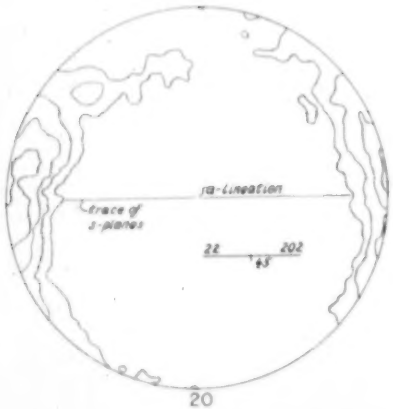
13



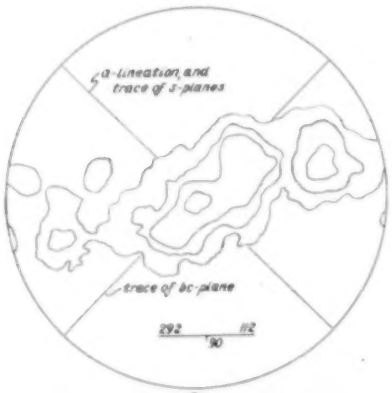
14



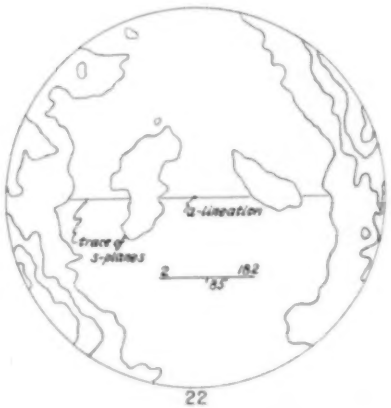
15



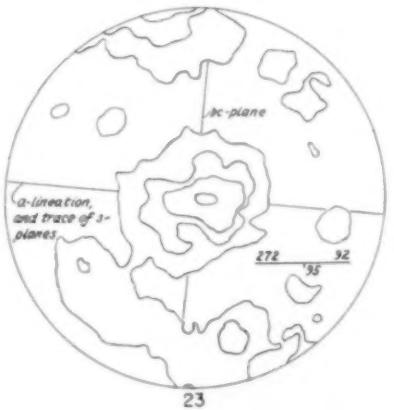
20



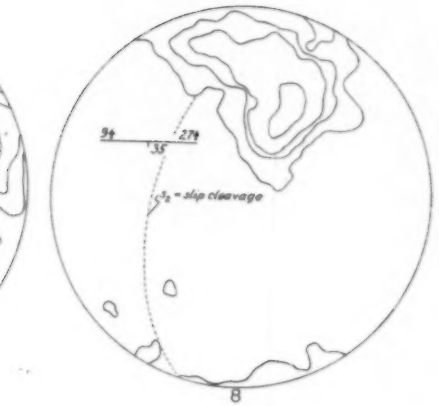
21



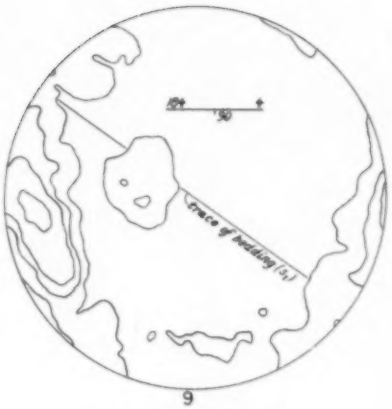
22



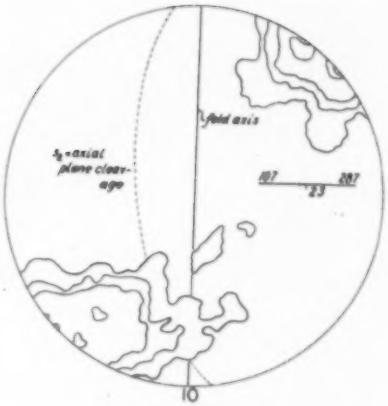
23



8

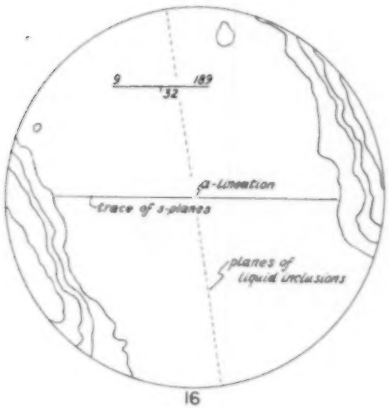


9

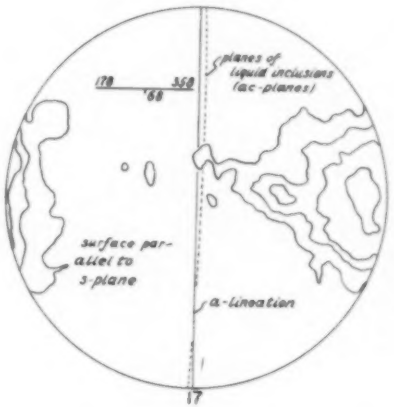


10

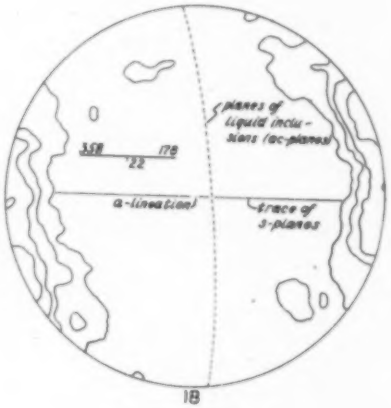
11



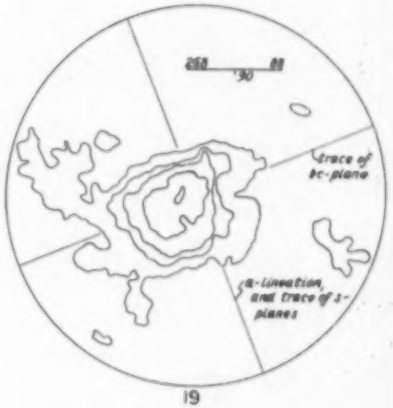
16



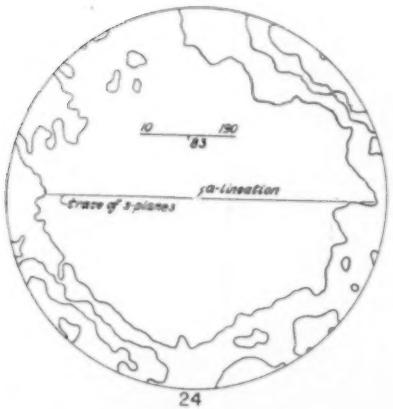
17



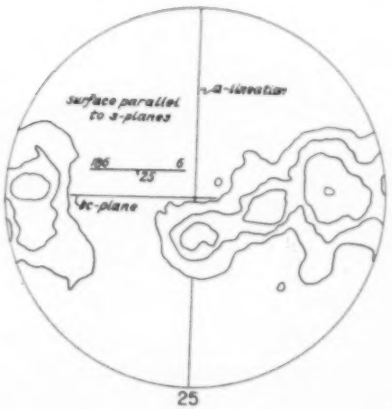
18



19

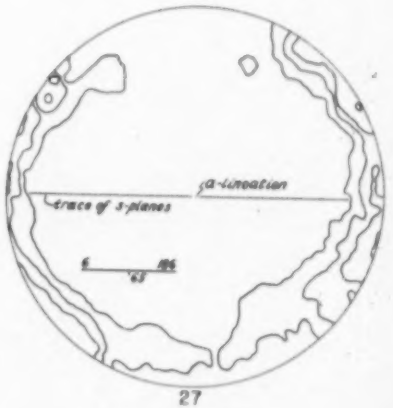


24



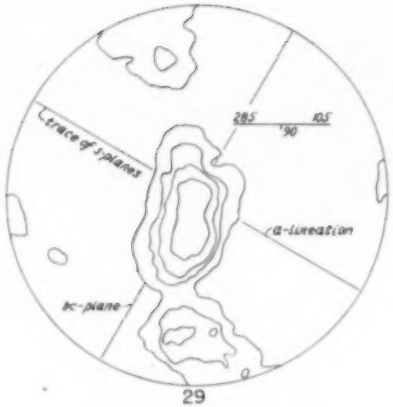
25

26

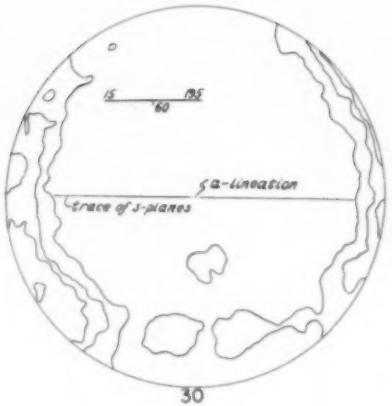


27

28

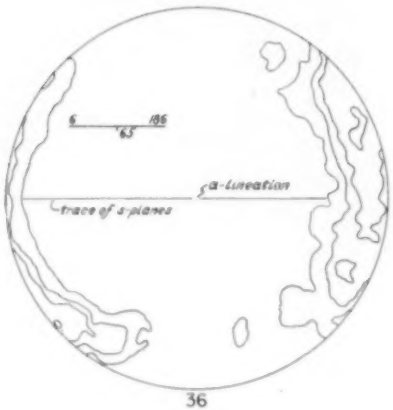


29

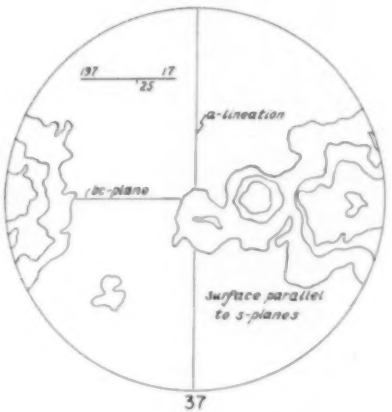


30

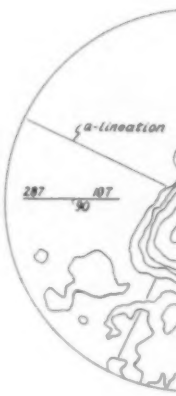
35

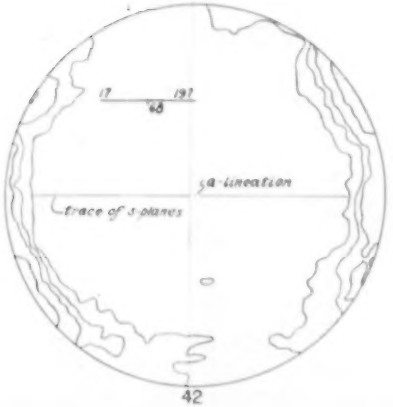


36

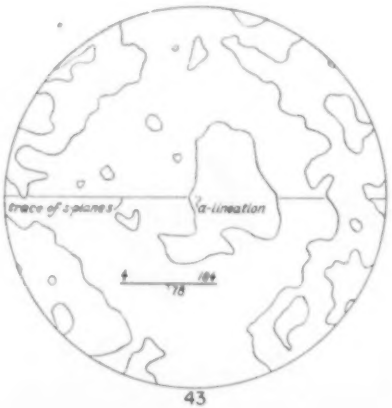


37



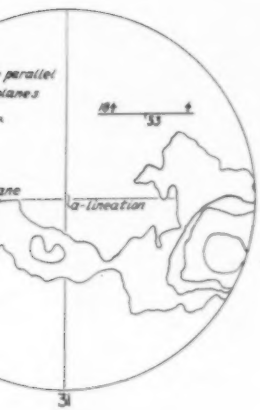


42

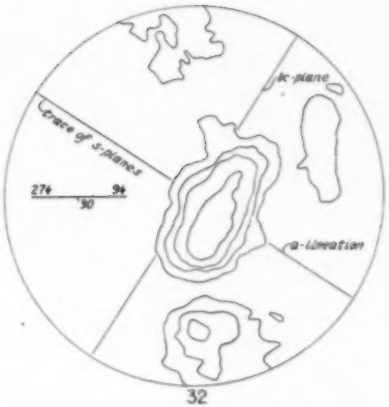


43

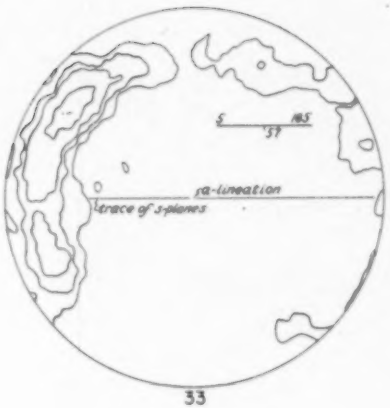
44



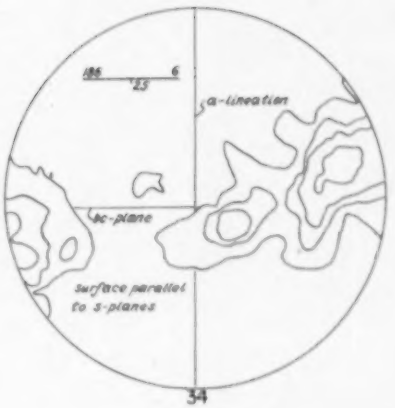
31



32

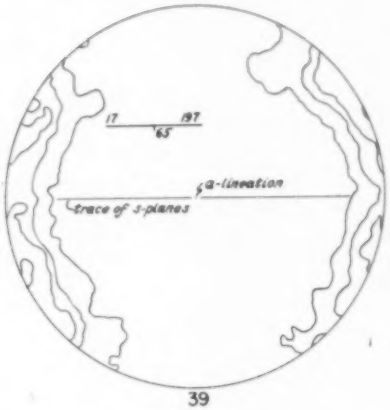


33

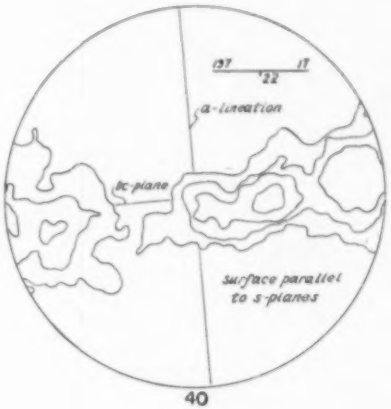


34

38



39



40

41

45

46

Figure	Location	Description
28	Same as 25, about 30 ft. lower in section	Section ‖ *s*-planes; incomplete girdle, about 30° steeper than *bc*-plane; maximum at 10 per cent
29	Same as 28	Section across *s*-planes, ‖ *a*-lineation; girdle 45° steeper than *bc*-plane; maximum at 15 per cent
30	Same as 28	Section across *s*-planes and *a*-lineation; girdle 30° steeper than *bc*-plane; maximum at 11 per cent
31	Same as 28, about 8 ft. lower in section	Section ‖ *s*-planes; incomplete girdle, about 25° steeper than *bc*-plane; maximum at 14 per cent
32	Same as 31	Section across *s*-planes, ‖ *a*-lineation; suggestion of incomplete girdle about halfway between *bc*-plane and *ab*-plane; maximum at 17 per cent
33	Same as 31	Section across *s*-planes and *a*-lineation; incomplete girdle, about 30° flatter than *bc*-plane; maximum at 13 per cent. Agreement with 32 poor
34	Same as 31, about 15 ft. lower in section	Section ‖ *s*-planes; incomplete girdle, 20° steeper than *bc*-plane; maximum at 13 per cent
35	Same as 34	Section across *s*-planes, ‖ *a*-lineation; incomplete girdle, 35° steeper than *bc*-plane; maximum at 22 per cent
36	Same as 34	Section across *s*-planes and *a*-lineation; incomplete *bc*-girdle; maximum at 11 per cent
37	Same as 34, about 10 ft. lower in section	Section ‖ *s*-planes; incomplete *bc*-girdle; maximum at 11 per cent
38	Same as 37	Section across *s*-planes, ‖ *a*-lineation; incomplete *bc*-girdle; maximum at 24 per cent
39	Same as 37	Section across *s*-planes and *a*-lineation; incomplete *bc*-girdle; maximum at 11 per cent
40	Same as 37, about 10 ft. lower in section and 200 ft. farther N. in scarp	Section ‖ *s*-planes; incomplete *bc*-girdle; maximum at 13 per cent
41	Same as 40	Section across *s*-planes, ‖ *a*-lineation; incomplete girdle about halfway between *bc*- and *ab*-plane; maximum at 22 per cent
42	Same as 40	Section across *s*-planes and *a*-lineation; incomplete *bc*-girdle; maximum at 13 per cent
43	NW. slope of the Dome, SW. Vt., 12 ft. below thrust fault	Micaceous arkose; section across *s*-planes and *a*-lineation; maximum at 4 per cent
44	Same as 40, apex of near-isoclinal, overturned syncline	Section ‖ axial plane (s_0), in same orientation as 25, 28, 31, 34, 37, and 40; incomplete *bc*-girdle of low concentration; much scattering of axes; maximum at 9 per cent
45	Same as 44	Section in vertical plane, across fold axis; trace of beds of lower limb, if represented, would be about horizontal; considerable scattering of axes; maximum at 9 per cent
46	Same as 44	Section dips W.–NW., ⊥ axial plane, ‖ axis of fold, in orientation comparable to that of 27, 30, 33, 36, 39, and 42; scattered areas of low concentration; maximum at 5 per cent

73) report the same degree of variation of measurable directions that is encountered in a few cases. However, in the more intensely deformed phases of the quartzite, the structural elements vary less in orientation.

The quartz fabric at the ledge northwest of Ellis Pond (figs. 13, 14), which may be about 30 feet above the basal unconformity, shows a strong (25 per cent) horizontal maximum that coincides with the *b*-fabric axis, striking north-northeast. The Tenmile River diagrams show at best a weak suggestion of girdles of *c*-axes, and the Ellis Pond rock has none at all.

STRONGLY DEFORMED QUARTZITE

All rocks of this group show a megascopic *a*-lineation, and fabric diagrams have strong maxima of *c*-axes, similar to those of the mildly deformed rocks. However, they reveal, in addition, girdles of *c*-axes, nearly complete or occupying arcs of appreciable width, that favor a position close to, or coinciding with, the *bc*-fabric plane.

At the Tenmile River locality two specimens were collected 4 and 9 feet, respectively, below the thrust fault (figs. 15–19). The *bc*-girdle of the rock 9 feet below the thrust covers about 90°, and the maximum plunges at about 30° to the north-northwest. The girdle in the specimen 4 feet below the thrust is wider, and in figure 19 its plane dips more gently than does the megascope *bc*-plane. The orientation of quartz *c*-axes at the thrust northwest of Ellis Pond is essentially the same (figs. 20, 21). Here, too, the girdle plane happens to lie about 30° flatter than the *bc*-plane as determined megascopically.

The same fabric elements are found in the quartzite below the exposed thrust at the Dome. Figures 22 and 23 are diagrams of normal quartzite, about 60 feet below the thrust plane, and figure 24 is of an arkose layer, about 45 feet below the thrust. Fabric maxima close to the *b*-direction and *bc*-girdles are clearly indicated in the arkose, though the girdle in the quartzite is too incomplete and weak to assign it to a plane close to *bc* rather than to an *ac*-plane.

A series of seven blocks was collected across the west-facing scarp, ¾ mile southwest of the Dome, and 21 sections were prepared. Three of them, however, could not be used, as the grains are very small and the section is so dusty with graphite that extinctions of quartz grains could not be determined with sufficient accuracy. The remainder, 18 diagrams, are shown in figures 25–42. Figure 50 gives the orientation of any 3 that were prepared from the same block. They are arranged from east to west and were collected at fairly equal distances across the exposed section of about 120 feet. The fabric in the six specimens is rather uniform. There is a girdle of *c*-axes in a plane about 30°–40° steeper than the fabric *bc*-plane, though in some diagrams the plane approaches the *bc*-plane closely, and diagrams 32, 35, and 38 suggest perhaps two girdles symmetrically disposed about the *bc*-plane. All girdles are incomplete, with fabric maxima, varying from 10 to 24 per cent, pointing in a northerly direction, with low plunge either to the north or to the south, thus approaching closely the regional *b*-direction. In the diagrams the direction *b* has not been marked because the specimens have neither a megascopic *b*-lineation nor fold axes in this direction left, as was explained before.

Thus 10 quartzite specimens, collected close to exposed or inferred thrust faults and distributed over 75 miles along the strike of the fault zone, ex-

hibit essentially the same fabric elements, including an incomplete girdle parallel to, or close to, the *bc*-plane, whereas, a few hundred feet from the same faults, such girdles may be lacking. We regard this as a strong suggestion that girdles close to the *bc*-plane have been brought about by the specific mechanism of deformation along thrust faults. In agreement with Kvale (1945), Strand (1944), and Cloos (1947), we must assume that the direction of thrusting, i.e., of tectonic transport, is perpendicular to the girdle plane.

MODIFYING FACTORS

One may ask to what extent the development of this fabric may be interfered with by other factors. Although this had been anticipated in the field, we have not investigated this matter in detail and merely draw attention to a few observations. Highly micaceous or feldspathic layers may be presumed to show fabrics differing from relatively pure quartzite. Likewise, it stands to reason that apices of folds, being rather resistant to deformation, may differ from surrounding laminated quartzite in the arrangement of fabric elements.

Figure 43 shows the quartz fabric in a highly micaceous arkose layer, 12 feet below the thrust fault on the northwest slope of the Dome. The highest concentration of axes is 4 per cent, and, although a *bc*-girdle is suggested, the axes are obviously much more scattered than in the corresponding diagrams of pure quartzites. In contrast, figure 24 shows a typical *bc*-girdle, although the rock is a highly feldspathic arkose layer, collected at the same group of ledges and farther from the same thrust fault than the rock of figure 43. Perhaps, then, a large amount of mica will interfere with the formation of a quartz fabric, whereas the presence of even an appreciable amount of feldspar does not.

The apex of a near-isoclinal syncline overturned to the west-northwest was found preserved in the quartzite scarp southwest of the Dome, about 600 feet north of the section from which the diagrams of figures 25–42 were prepared. The axis of the fold strikes N. 27° E. and lies horizontally; the lower limb is nearly horizontal, and the upper limb dips east-southeast at about 70° where it curves around the axis. Axial-plane cleavage, not visible at the apex proper but noticeable a few feet away, dips east-southeast at 42°, whereas at the apex a second, crude cleavage (s_3) dips at about 88° east-southeast. The specimen lacks the *a*-lineation so prominent near by. Under the microscope the rock reveals a large amount of feldspar, and the s_3 cleavage consists of discontinuous zones of closely packed feldspar grains with a generous admixture of opaque minerals, presumably pyrite, magnetite, or both. From this specimen three mutually perpendicular sections were cut, one (fig. 44) parallel to the axial plane, the second (fig. 45) in a vertical plane at right angles to the fold axis, and the third (fig. 46) parallel to the fold axis, dipping west-northwest at right angles to the axial plane. The three surfaces are thus oriented in the same directions as are those of the quartzite specimens near by. A 9 per cent maximum is shown in the first two sections. The maximum of figure 44 points in a direction N. 137° E., with a northwesterly plunge of about 38°. The second one has a horizontal maximum in a direction N. 3° E. Both have a spread of about 20°. The 5 per cent maximum of the third section could be correlated with that of the first one. In the specimen these two sections are closer to each other than to the second one with its

horizontal north-south maximum. But beyond this poor correlation it is difficult to find much similarity between the three fold diagrams and those of the laminated quartzite. A *bc*-girdle is suggested in figure 44, but it lacks the concentration of the other diagrams, and in figures 45 and 46 the axes are even more scattered.

These few observations do not permit a definite answer to the questions before us. A large amount of mica and the complicated system of slip and rotational movements that may be envisaged at apical zones of folds would seem to interfere with the normal formation of girdle-and-maximum fabric of the purer quartzite, but to what extent, and up to what limiting conditions, we do not know.

DEFORMATION LAMELLAE AND PLANES OF LIQUID INCLUSIONS

Deformation lamellae seem to be nearly absent in the rocks examined. They were noted in larger numbers only in sections from quartzite at the Tenmile River locality in the specimen 12 feet above the unconformity. Here the lamellae have a fairly uniform orientation, dipping about 70° in a westerly direction. As they were observed but sporadically in other thin sections, no effort was made to determine whether they should be classed with deformation lamellae or with deformation bands, as distinguished by Riley (1947, pp. 461–470).

Planes of liquid inclusions were noted in several specimens (pl. 1, *B*, *C*). At both Dutchess County and Vermont localities the planes follow closely the *ac*-fabric planes: they strike about east-west and are nearly vertical, in agreement with observations by Tuttle on the orientation of these microscopic features near Washington, D.C. (1949, pp. 346, 347, fig. 30). That the planes follow an areal direction of strain and are independent of the crystallographic orientation of the host grains is shown particularly well in thin sections close to thrust faults, for example, at the Tenmile River locality, where the *ac*-planes penetrate not only quartz grains of diverse orientation but microcline grains as well (pl. 1, *C*), in the same east-west direction. It is probably significant, also, that planes of liquid inclusions in undisturbed quartzite, northwest of the Dome, show some alignment in a north-south direction which was nowhere seen in the entire belt of severely deformed quartzite.

TEXTURE

As the work progressed, it became clear that not only the fabric orientation but the texture, as well, undergo systematic changes where mildly deformed quartzite is followed into severely deformed zones.

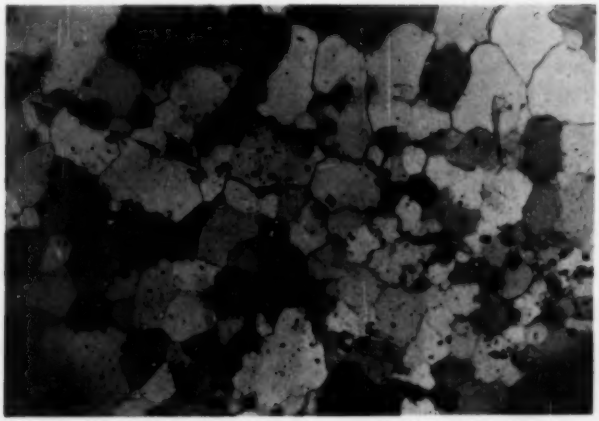
A slight but constant elongation of a fair proportion of quartz grains parallel, or close, to the *b*-fabric direction is seen in virtually all slides of the mildly deformed rock (pl. 2, *A*, *C*, *D*). Even 4 feet

PLATE 1

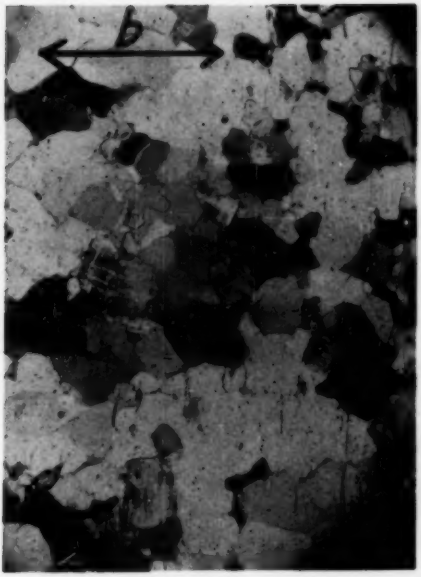
A, Streak of zircon, feldspar, magnetite, and apatite, parallel to *a*, enclosed by unstrained quartz grains elongated parallel to *b*. Same specimen as that of plate 3, *B*; *ab*-surface; crossed nicols. ×39.

B, Planes of liquid inclusions parallel to *ac*-planes, penetrating unstrained quartz grains in various orientations elongated slightly parallel to *b*. Quartzite 4 feet below thrust fault, east of Tenmile River; *ab* (=*s*)-surface; crossed nicols. ×39.

C, Planes of liquid inclusions parallel to *ac*-planes, penetrating both quartz and microcline grains in the same direction. Same locality as that of *B*; *ab*-surface; crossed nicols. ×39.



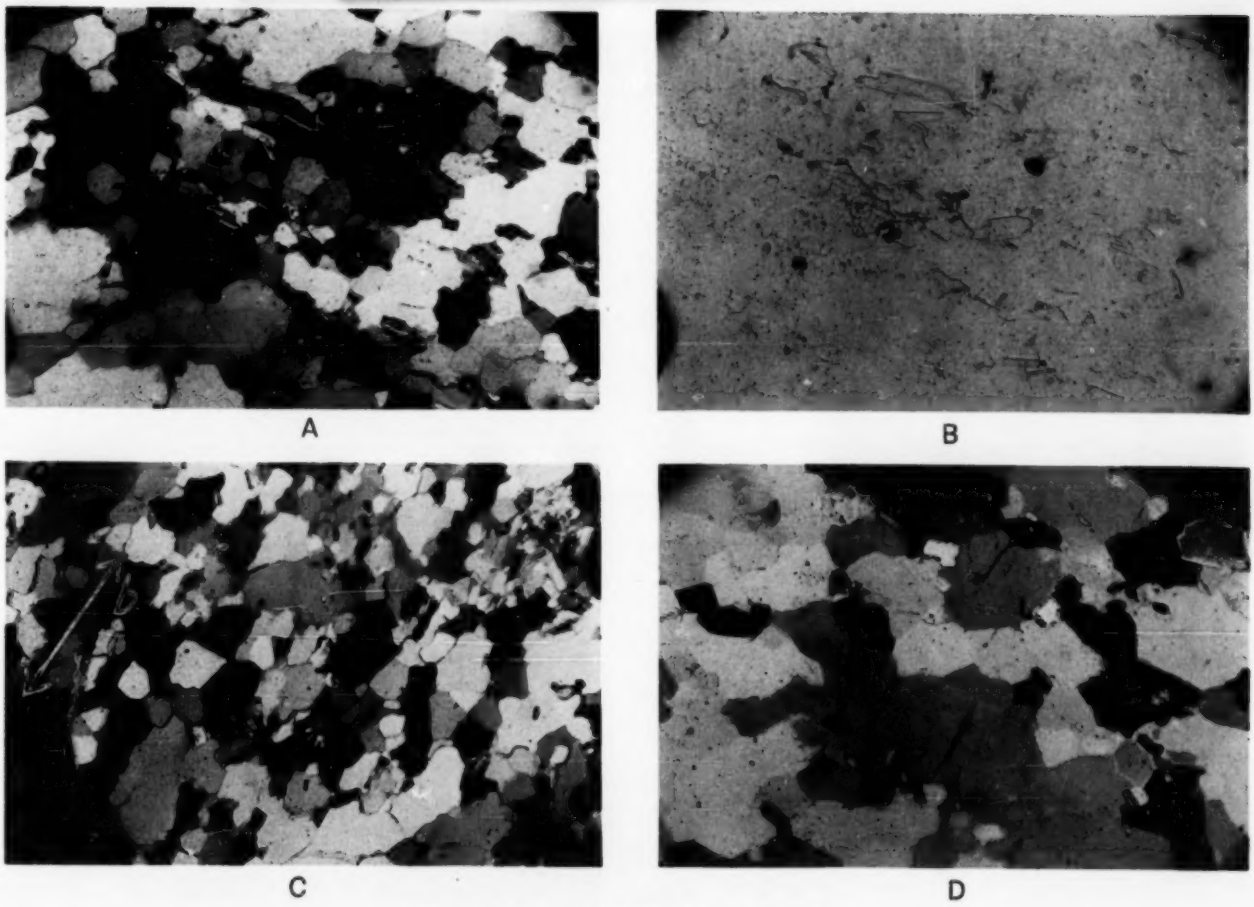
A



B

C

Mineral streaks and planes of liquid inclusions



Elongation of quartz in mildly deformed quartzite

above the basal unconformity, east of Tenmile River, where megascopically the deformation of the quartzite is negligible, the microscope reveals the elongation here and there. Twelve feet above the base, where the layers are slightly flexed and axial-plane cleavage and *b*-lineation can be seen megascopically, the elongation is more pronounced (pl. 2, *A*). At the crest of the open, broad fold northwest of Ellis Pond, the elongation is also seen, even though cleavage is quite elusive (pl. 2, *D*).

When thin sections of quartzite with *a*-lineation are examined, it is somewhat of a surprise to find that the bulk of the quartz grains remains elongated parallel to the *b*-fabric axis, although Kvale (1945, p. 198) mentions the same transverse elongation of quartz from the Norwegian thrust zone. As is common, the direction of elongation lies close to the crystallographic *c*-axis of each grain. Dimensions of these quartz grains average as follows: parallel to the fabric *a*-axis, about $\frac{1}{4}$ mm.; parallel to the fabric *b*-axis, about $\frac{1}{4}-\frac{1}{3}$ mm.; and parallel to the fabric *c*-axis, about $\frac{1}{15}$ mm.

The megascopic *a*-lineation is produced by streaks of feldspar, muscovite, magnetite, pyrite, zircon, tourmaline, garnet, sphene, and apatite, in various proportions and combinations (pls. 1, *A;* 3). When these tracts are viewed under crossed nicols and a gypsum plate inserted, the quartz grains between the associated silicates in the *a*-tracts exhibit contrasting optical orientation from the bulk of quartz grains in the rock. In the 45° position, for example, the bulk of the quartz grains may be green, while the quartz grains in *a*-tracts are red, and vice versa. Away from thrust faults, the *a*-tracts of quartz and other silicates become more elusive (pl. 3, *A*). In specimens some 400–500 feet below a thrust, we were unable to find them under the microscope, though megascopically the rock may still show a faint *a*-lineation.

It is interesting that feldspar grains in *a*-tracts have not undergone plastic deformation during the shearing and thrusting that produced the quartzite texture. Instead, they have fractured, and a majority of the fractures are *bc*-cracks, by which the aggregate has been lengthened parallel to the thrusting direction. Quartz has entered the fractures and crystallized as thin plates (pl. 4, *A*). Where feldspar fragments have moved apart, the quartz grains between them have grown to larger size, resembling feather quartz (pl. 4, *B*). Commonly, feldspar grains have been faulted internally on a minute scale and are surrounded by strain-free quartz grains flattened parallel to the curved outline of the feldspar mosaic (pl. 4, *C*). Where

---

PLATE 2

A, Slight elongation of quartz grains in horizontal north-northeast direction (left to right). Muscovites, representing bedding = s_1, dip 20°–30° steeper to the north-northeast. Photograph taken looking west-northwest. Compare fig. 9. Quartzite 12 feet above unconformity, east of Tenmile River; 7½′ Dover Plains Quadrangle, New York–Connecticut; crossed nicols. ×39.

B, Same area as *A;* plain polarized light, showing northerly dip of muscovite plates. ×39.

C, Elongation of quartz grains parallel to *b*, more marked than in *A*. Same locality, 45 feet closer to nearest thrust, about same distance above unconformity; looking west; crossed nicols. ×39.

D, Elongation of quartz grains parallel to *b;* and *ac*-cracks, across elongation direction, in nearly vertical west-northwest planes. Quartzite about 30 feet above unconformity, at crest of gentle anticline, northwest of Ellis Pond, 7½′ Dover Plains Quadrangle, New York–Connecticut; looking west-northwest; crossed nicols. ×39.

s-planes of arkose are exposed to view close to thrust planes, as, for example, northwest of the Dome, one can see thousands of white streaks of feldspar, as much as 2 or 3 inches long, rigidly parallel to the *a*-direction.

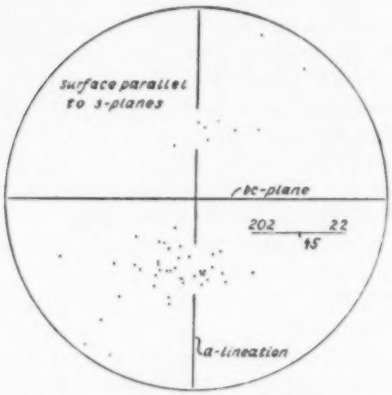


FIG. 47.—Orientation of *c*-axes of 50 quartz grains in *a*-tracts in quartzite at thrust fault northwest of Ellis Pond.

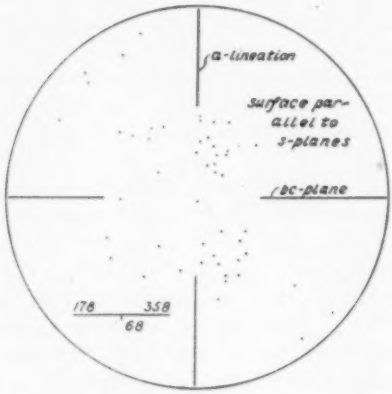


FIG. 48.—Orientation of *c*-axes of 53 quartz grains in *a*-tracts in quartzite 4 feet below thrust fault east of Tenmile River.

Systematic plotting of the *c*-axes of quartz in the *a*-tracts was beyond the scope of this study. However, in order to have a general check on the crystallographic orientation of the grains, three thin sections were studied, one from the Ellis Pond thrust (fig. 47), one at the Tenmile River thrust (fig. 48), and one at the Dome Mountain thrust zone (fig. 49). In all three specimens the *c*-axes of the quartz grains form high angles with the *ab* (=megascopic *s*-)-plane, and two (figs. 47 and 48) may possibly have two maxima or even a tendency toward a girdle close to the *ac*-fabric plane. More detailed study is likely to verify these alternatives. Quartz grains belonging to the *a*-tracts of silicates are much fewer than those of opposite orientation outside the tracts, and for this reason the contrasting orientation of the grains in the *a*-streaks does not show up in the

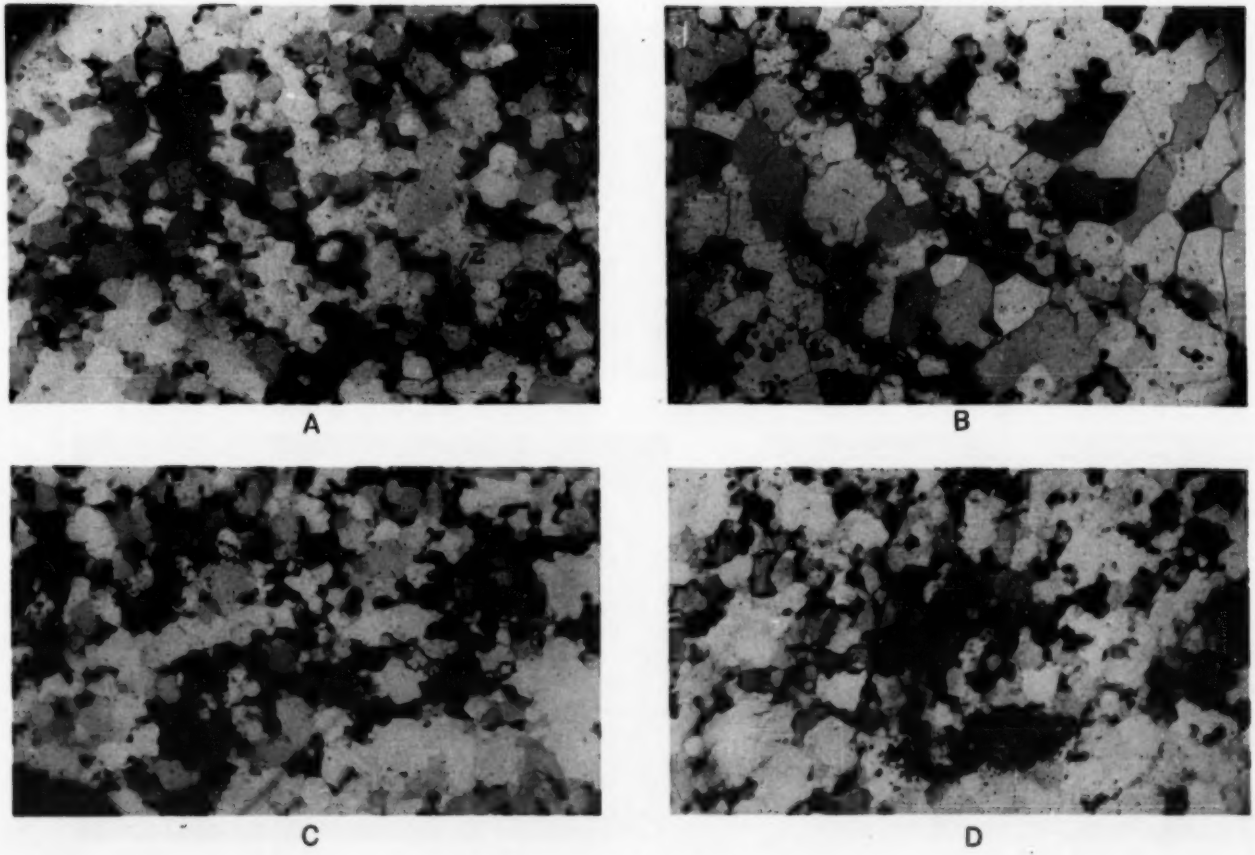
PLATE 3

A, Elusive streak of quartz grains parallel to *a* (*dark*, from upper left to lower right), surrounded by quartz groundmass having contrasting orientation. At lower right, in line with *a*-tract of quartz, a zircon (*z*) and a feldspar grain (*f*). West-facing scarp southwest of the Dome, 15′ Bennington Quadrangle, Vermont; same *ab* (=*s*)-surface as that of fig. 28; crossed nicols. ×39.

B, Tracts of feldspar, zircon, muscovite, and quartz parallel to *a*, across quartz groundmass of relaxed grains elongated parallel to *b*. About 30 feet below thrust fault, northwest of Ellis Pond; *ab*-surface; crossed nicols. ×39.

C, Tract of quartz with minor amounts of feldspar and muscovite (*dark grains*, parallel to long edge of picture) parallel to *a*. Specimen about 33 feet below that of *A*; same *ab* (=*s*)-surface as that of fig. 37; crossed nicols. ×39.

D, Streak of magnetite dust (*bottom, middle part*) parallel to *a*, accompanied by tract of quartz and feldspar in same direction (*dark grains* near center of picture). Specimen about 23 feet below that of *A*; same *ab* (=*s*)-surface as that of fig. 34; crossed nicols. ×39.



Streaks of minerals parallel to thrust movement

Fractured feldspar near thrusts

ordinary fabric diagrams of the same thin sections (figs. 20, 21, 17, 37). It is interesting, also, that a number of quartz grains in *a*-tracts are somewhat elongated parallel to the streaks, though they do not develop into "feathers" or

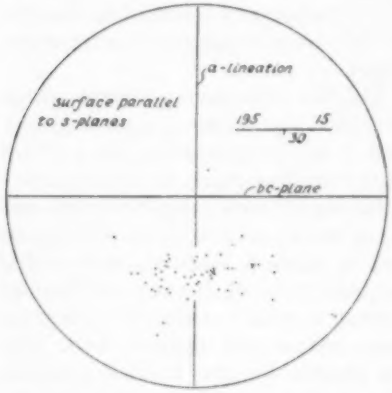


FIG. 49.—Orientation of *c*-axes of 60 quartz grains in *a*-tracts in quartzite scarp, ¾ mile southwest of the Dome.

fibers, as is seen where the groundmass of crystalline schists has receded from crystalloblasts during deformation.

As noted above, the thrust faults at the west-facing scarp of quartzite, southwest of the Dome, are concealed, and it had been our hope that a fabric study of the rocks might help to locate them more accurately. The fabric diagrams (figs. 25–42) do not differ sufficiently to permit such a decision. However, the *a*-lineation is markedly stronger in the westernmost, i.e., structurally lower, zone (pl. 3, *A*–*C*); and this textural feature, combined with the associated *bc*-girdle of *c*-axes, is tentatively regarded as a strong suggestion that a thrust is concealed at the west base of that scarp. If another thrust is located east of the scarp, it would seem to be sufficiently remote that the intensely laminated and streaked zone associated with it lies east of the present exposures, buried under till.

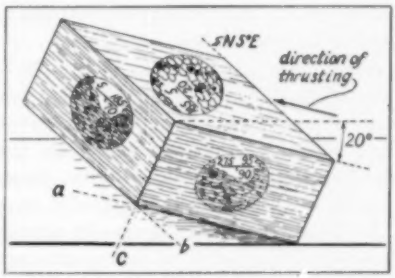


FIG. 50.—Block diagram showing general orientation of quartzite close to thrust faults. Only megascopically visible system of *s*-planes dips easterly; prominent *a*-lineation coincides with direction of thrusting. Insets show texture on three mutually perpendicular principal sections through rock. Bulk of quartz grains elongated slightly parallel to *b*, crossed by *a*-tracts of feldspar, mica, etc., and quartz with crystallographic orientation distinct from bulk. Figures in insets give orientation of thin-section surface.

INTERPRETATION OF DATA

In order to picture the mechanism through which the rocks have acquired their fabric, we may review the following

PLATE 4

A, Microcline grain, faulted into numerous fragments, surrounded by unstrained, recrystallized quartz grains flattened parallel to feldspar surface. Micaceous arkose 12 feet below thrust fault, northwest slope of the Dome; crossed nicols. ×39.

B, Large microcline grain distended parallel to *a* and fractured into two fragments, m_1 and m_2, joined by narrow plates of quartz elongated parallel to *a*. Arkose 45 feet below thrust fault, northwest slope of the Dome; crossed nicols. ×39.

C, Microcline grain (*dark, in center*) elongated parallel to *a*, fractured across, and filled with quartz *bc*-plates (*narrow white dashes*). Same locality as *B*; *ab*-surface of arkose; crossed nicols. ×39.

points that appear reasonably well established:

1. Even a megascopically small deformation, barely sufficient to buckle the layers of deposition, seems adequate to alter profoundly, perhaps even to destroy, the primary granular texture and fabric of the quartzite. This was seen at the Ellis Pond and Tenmile River outcrops, where strong fabric maxima close to *b* appear in nearly flat-lying beds. A scarcely perceptible axial-plane slip cleavage in these rocks may, therefore, indicate some very extensive rearrangement of the rock fabric.

2. At this stage the most stable shape of quartz grains seems to be a triaxial ellipsoid, flattened parallel to the axial plane, slightly elongated in the *b*-fabric direction, and about four times wider in the *ab*-plane than parallel to *c*.

3. Minerals other than quartz remain randomly distributed in the quartz aggregate, and elongation of the quartz grains parallel to *b* is the only linear feature noticeable in the *ab*-fabric plane.

4. Planes of liquid inclusions are rare, but those that appear prefer the *ac*-fabric plane, regardless of the crystallographic orientation of the host.

5. Whether deformation lamellae have been important in facilitating the rearrangement of quartz grains is unknown. If they were, the final recrystallization of the quartz grains must have all but eliminated their traces.

6. Close to thrust planes, three special fabric elements make their appearance:

a) The *c*-axes of quartz tend to develop *bc*-girdles, and the grains remain elongated slightly in directions close to the *b*-fabric axis.

b) Planes of liquid inclusions parallel to the *ac*-fabric plane are abundant in many places; the cracks penetrate not only quartz grains in random orientation but other silicates as well, notably feldspar.

c) In zones of intense deformation, silicates other than quartz have fractured in brittle condition and have been drawn out in streaks parallel to *a*. Quartz grains associated with these *a*-tracts prefer crystallographic orientations that differ from those of the surrounding quartz grains.

The last three points deserve special attention. The strain of a plate of rock that is being deformed along a thrust fault resembles closely the mechanics of technological rolling, especially the rolling of metals. A few significant aspects may be recalled. When an ingot of steel has been prepared, it must pass through a series of rolls in order to acquire the cross section and general shape that are desired for the finished material. Where sheet metal is produced, the effect of each "pass" is largely to depress the height of the block. The ingot thereby becomes thinner, but it also widens parallel to the axes of the rolls, and, at every pass, the block is elongated most in the direction of rolling. If it is desired to prevent the widening of the block parallel to the axes of the rolls, lateral constraints must be provided, as, for example, when T-beams, rails, or other goods are manufactured that have a "profile." Without these lateral constraints, the initial deformation is triaxial, and the ratios of deformation in the three directions are known to vary considerably, depending upon the thickness of the sheet, the percentage of compression at a given pass, the temperature of the block, the temperature gradient within the block, the curvature of the rolls, the speed of rotation of the rolls, the type of alloy crystals, and their fabric (Camp and Francis, 1940, pp. 616, 644, 645).

When the ingot is still hot, it contains a certain amount of gases and slaggy material. Some of this has a lower melting point than the metal and is squeezed out of it as the ingot moves through the first or second pass (Meissner, 1910, p. 287). The remainder, however, consists of refractory substances, especially carbides, sulfides, and certain oxides, the melting points of which lie appreciably higher than those of the metal. When the ingots or billets (ingots already passed through the first roll) move past the rolls, these hard impurities move at slightly different speeds from that of the surrounding alloy crystal grains (Goerens, 1926, p. 334; Puppe and Stauber, 1929, p. 647; Oberhoffer, 1936, p. 422), and, owing to rotational movements on their boundaries, they arrange themselves into streaks or rows of grains parallel to the rolling direction, which is always the direction of maximum elongation. This imparts to the mass a "coarse" rolling texture (as opposed to a much finer rolling texture in which certain crystal faces, or crystallographic symmetry directions, take on a preferred orientation at the last stages of rolling; see Barrett, 1943, pp. 395–416). It has been described and illustrated in many handbooks of metallurgy (Gredt, 1923, p. 1448; Puppe and Stauber, 1929, p. 410, figs. 150, 151, p. 647; Sauveur, 1935, pp. 185, 192, 193, figs. 152, 161, 162; Oberhoffer, 1936, fig. 509, p. 421, fig. 492). It is emphasized that even exceedingly small amounts of these impurities are sufficient to impart to the whole sheet a fibrous texture parallel to the rolling direction (Oberhoffer, 1936, p. 422, fig. 512), and, as it is almost impossible to remove the last traces of these refractory substances, the rolling texture of this kind is so ubiquitous that one of the chief purposes of annealing is to eliminate it. If many impurities are present, if the billet has been rolled too fast or at too low a temperature, or if a combination of these factors has operated, the rolled sheet may rupture along fractures across the rolling direction.

Obviously, the "coarse" rolling texture of metals resembles that of quartzites and arkoses close to thrust faults in many important aspects. But it may be worth while to mention a few additional points on which, at present, information is incomplete but which may help to explain a few other features. We find, in the quartzites here described, a seemingly contradictory association of two directions of elongation: the one parallel to *b*, exhibited by the bulk of quartz grains; the other parallel to *a*, as shown by the tracts of refractory silicates with associated quartz. Now one would expect that the details of distortion of a steel sheet, under the simplified and closely controlled conditions of a rolling mill, would be extremely well understood. But reference to the metallurgical literature shows that the process is so complicated that not every detail is understood. From 1910 on, following experiments by the French metallurgist, N. Metz, many elaborate attempts have been made to determine the amounts of distortion in the three mutually perpendicular directions. In several laboratories rows of bolts or screws were driven into steel blocks prior to rolling. After passing through the rolls, the deformed sheets were sliced through along vertical planes, and the degree of curvature of the distorted bolts, as seen on the polished and etched surfaces, gives a measure of the distortion in specific directions (Falk, 1912; Trinks, 1915; Gredt, 1923; Tafel and Sedlaczek, 1925; Tafel and Pajunk, 1927; Weiss, 1928; Puppe and Stauber, 1929, pp. 636–637; Hilterhaus, 1930).

These and similar experiments have shown that the rates of distortion vary at different levels within the rolled sheets, so that not only would models of deformation ellipsoids, if placed through a sheet, be triaxial, but their axial ratios would differ vertically. In intermediate levels between the rolls, the expansion parallel to the axes of the rolls can be appreciable, and it is interesting to note that, with these differences in distortion ratios, there are associated differences in the preferred orientation of crystals (Gensamer and Mehl, 1936; Wassermann, 1939, p. 85). It is unfortunate that the "coarse" rolling texture is of so little practical importance to metallurgists that we have been unable to find any detailed investigations into preferred crystallographic orientation or grain shape of metals in these relatively early stages of rolling. We regard it as possible, however, that at intermediate levels in the treatment of a billet there may well be groups of crystals elongated parallel to the axes of the rolls, corresponding to a *b*-elongation of quartz grains. Finally, it is reported by Goerens (1926, p. 335, figs. 383, 384) that in low-carbon steels there is a tendency for late-growing ferrite crystals to attach themselves to impurities, so that they grow preferentially among these streaks. Unfortunately, no information is given on the crystallographic orientation of these ferrite grains as compared with the surrounding grains. Reading the description, however, makes one wonder whether some of the quartz grains in *a*-tracts of refractory silicates may have acquired their special orientation by growing attached to surfaces of feldspar. If the observations by Laves (1939) are applicable to these conditions, one might imagine that the *c*-axes of these quartz crystals oriented themselves preferentially in the direction of greatest tension, which is *a*, and rotation of the feldspar grains may subsequently have brought a certain number of these quartz grains with their *c*-axes into the *ac*-fabric plane. It is true, as Fairbairn (1950*a*) points out, that feather quartz may not show any preferred crystallographic orientation, but perhaps the growth of these relatively stubby grains varied from that of typical fibrous quartz feathers around crystalloblasts.

If a sheet of hot steel less than 1 inch thick, treated under the closely controlled conditions of a rolling mill, exhibits complex differences in directions and amounts of distortion throughout its cross section, how much more complicated must be the deformation of an aggregate of silicates under an actively moving thrust sheet! It has, as support, not a carefully smoothed and polished surface of uniform composition, but a mosaic of materials differing in strength and mechanical stability. Inhomogeneous layers, lenses, as well as irregularly shaped masses of rock, some rupturing, others in the field of plastic flow, are engaged in nearly, but not quite, parallel directions of movement. A temperature gradient, circulating solutions, and recrystallization, acting over a presumably long period of time, are likely to have done their part in making the movement of the whole mass highly complex. In view of these numerous complicating factors, it is remarkable that the structural features close to the thrust planes here discussed do not vary more than they do. We assume that close to the main dislocation surface the shearing strength of quartz (though not that of feldspar and several other silicates) was so generally overcome that the quartzose rocks became fairly homogeneous mechanically and thus acquired a rather uniform tex-

ture and grain orientation, at least during the stage of final recrystallization.

The *a*-lineation has a close analogue in the coarse rolling texture of steel and, it may be remarked parenthetically, of rolled glass in which the scattered air bubbles are also elongated parallel to the rolling direction. We are still in need of fabric data on rolled steel indicating similarity to the predominant parallel, or nearly parallel, elongation of the quartz grains to the *b*-fabric direction. We suspect that, if it were possible to obtain information on the texture of those layers of rolled alloys that have registered appreciable widening parallel to the axes of the rolls, some similar feature would be discovered. Even though elongation parallel to *b* is appreciably less than that parallel to *a* in the intensely deformed zones, it remains a factor that must be considered. In fact, Oftedahl (1948, pp. 485–486) has shown that the total elongation in *b* can be considerable. We must probably assume that the grains were somehow rotated in the *bc*-plane in order to acquire the observed girdles of *c*-axes, a process that has been likened by Cloos (1947, p. 11) to the rocking and swaying experienced by a traveler in a moving train.

This brings us to a final point: the scale on which observations are made. In the field we may observe and record the so-called "megascopic" deformation directions, and, where pebbles and boulders or oöids are available, we may even measure them quantitatively. However, it is not necessary to assume that all fabric elements are arranged in identical directions on the much smaller scale of a microscopic thin section or, for that matter, before the X-ray camera. As an example, we may mention the relationship between cross-joints and *ac*-planes of liquid inclusions in the quartzite. In outcrops in which these microscopic fractures are very abundant, there are, nevertheless, relatively few joints in the same direction. Tuttle (1949, p. 353) reports the same discrepancy. Conversely, the ledges of quartzite with *a*-lineation commonly display cross-joints perpendicular to *a*, but *bc*-cracks under the microscope are relatively rare. Even in the most highly deformed specimens they appear best where they penetrate refractory feldspar grains. Elongation of quartz parallel to *b* is not visible megascopically in exposures close to thrust faults; yet the microscope leaves no doubt that it is a widespread structure element. As the rolling process shows, there is some expansion of the sheet parallel to the axes of the rolls, even though the typical rolling texture emphasizes only the *a*-direction. Under the circumstances, it seems best to regard the *b*-elongation of the quartz grains as caused by distortion parallel to *b*, whatever its true nature may have been.

In conclusion, the study of the suite of quartzite specimens seems to leave little doubt that the combination of a strong *a*-lineation with complete or incomplete *bc*-girdles of quartz and the texture of the quartz aggregate as described are significant products of the intensive deformation that rocks have undergone close to thrust faults. We regard further detailed investigations of these problems as important and rewarding. Many ways come to mind that may advance our knowledge. Recently, Fairbairn (1950*b*) began experiments designed to fix individual stages by which sand is deformed into quartzite. It will be most interesting to learn what an aggregate of quartz sand will do when shear stress is added to compressive stress, in the presence of $(OH)^-$ ions. Similarly, the new investigation by Sander (1950, pp. 161–217) of

the distribution of axis orientation in parallel layers of rock promises much new insight into the mechanism by which various directions of slip, rotation, and shear planes co-operate with one another, but in different combinations at different levels. Sander's beautiful colored plates (1950, pls. I–IV), accompanied by photomosaics of the same areas, are most illuminating. Combined, we hope, with more pertinent data from metallurgy, such comparative studies may bring to light closer similarities between rolled metals and rocks deformed by thrusting than we can prove at present.

REFERENCES CITED

BALK, ROBERT (1936) Structural and petrologic studies in Dutchess County, New York. Pt. 1: Geologic structure of sedimentary rocks: Geol. Soc. America Bull. 47, pp. 685–774.

BARRETT, C. S. (1943) Structure of metals, New York, McGraw-Hill Book Co., Inc., 567 pp.

CAMP, J. M., and FRANCIS, C. B. (1940) The making, shaping and treating of steel, 5th ed., 2d impression, Carnegie-Illinois Steel Corp., Pittsburgh-Chicago, 1440 pp.

CLOOS, ERNST (1946) Lineation, a critical review and annotated bibliography: Geol. Soc. America Mem. 18, 133 pp.

——— (1947) Tectonic transport and fabric in a Maryland granite: Soc. géol. Finlande Compte rendu 20, 14 pp.

——— and HIETANEN, ANNA (1941) Geology of the "Martic overthrust" and the Glenarm series in Pennsylvania and Maryland: Geol. Soc. America Special Paper 35, 207 pp.

FAIRBAIRN, H. W. (1949) Structural petrology of deformed rocks, Cambridge, Addison-Wesley Press, Inc., 344 pp.

——— (1950a) Pressure shadows and relative movement in a shear zone: Am. Geophys. Union Trans., vol. 31, pp. 914–916.

——— (1950b) Synthetic quartzite: Am. Mineralogist, vol. 35, pp. 735–748.

FALK, ADOLF (1912) Die Theorie der Materialwanderung beim Walzen und Schmieden: Stahl und Eisen, vol. 32, pp. 816–822.

FELLOWS, R. E. (1943) Recrystallization and flowage in Appalachian quartzite: Geol. Soc. America Bull. 54, pp. 1399–1432.

GAIR, J. E. (1950) Some effects of deformation in the central Appalachians: Geol. Soc. America Bull. 61, pp. 857–876.

GENSAMER, M., and MEHL, R. F. (1936) Preferred orientations produced by cold-rolling low-carbon sheet steel: Am. Inst. Min. Met. Eng. Trans., Tech. Pub. 704, 14 pp.

GOERENS, PAUL (1926) Einführung in die Metallographie, 5th ed., Halle an der Saale, Wilhelm Knapp, 372 pp.

GREDT, GEORG (1923) Über die Materialverschiebung beim Walzen: Stahl und Eisen, vol. 43, pp. 1443–1449.

HILTERHAUS, H. (1930) Der Einfluss des Seitendruckes auf die Formänderung beim Walzen und die Güte des Werkstoffes: Stahl und Eisen, vol. 50, pp. 1185–1194, 1221–1229.

KNOPF, E. B. (1936) Recognition of overthrusts in metamorphic terranes: Am. Jour. Sci., vol. 30, pp. 198–209.

KVALE, ANDERS (1945) Petrofabric analysis of a quartzite from the Bergsdalen quadrangle, western Norway: Norsk geol. Tidsskr., vol. 25, pp. 193–215.

LAVES, FRITZ (1939) Über den Einfluss von Spannungen auf die Regelung von Quarz- und Cristobalit-Kriställchen in Chalzedon, Quarzin und Lussatit: Die Naturwissenschaften, vol. 27, pp. 705–707.

MEISSNER, H. (1910) Untersuchung von Walzmaterial in den verschiedenen Verarbeitungsstufen: Stahl und Eisen, vol. 30, pp. 287–290.

OBERHOFFER, PAUL (1936) Das technische Eisen, Berlin, Julius Springer (republished by Edwards Bros., Ann Arbor, 1946), 738 pp.

OFTEDAHL, CHRISTOFFER (1948) Deformation of quartz conglomerates in central Norway: Jour. Geology, vol. 56, pp. 476–487.

PHILLIPS, F. C. (1937) A fabric study of the Moine schists: Geol. Soc. London Quart. Jour., vol. 93, pp. 581–620.

PUPPE, J., and STAUBER, F. (eds.) (1929) Handbuch des Eisenhüttenwesens. Vol. 1: Walzwerkswesen, Düsseldorf, Verlag Stahleisen, 780 pp.

RILEY, N. A. (1947) Structural petrology of the Baraboo quartzite: Jour. Geology, vol. 55, pp. 453–475.

ROWLAND, R. A. (1946) Grain-shape fabrics of clastic quartz: Geol. Soc. America Bull. 57, pp. 547–564.

SANDER, BRUNO (1950) Einführung in die Gefügekunde der geologischen Körper. Vol. 2: Die Korngefüge, Vienna and Innsbruck, Springer Verlag, 409 pp.

SAUVEUR, ALBERT (1935) The metallography and heat treatment of iron and steel, New York, McGraw-Hill Book Co., Inc., 535 pp.

STRAND, TRYGVE (1944) Structural petrology of the Bygdin conglomerate: Norsk geol. Tidsskr., vol. 24, pp. 14–31.

TAFEL, W., and PAJUNK, G. (1927) Ermittelung des Breitungsverlaufes in den wagerechten Schichten von Walzkörpern: Stahl und Eisen, vol. 47, pp. 1562–1565.

——— and SEDLACZEK, E. (1925) Das Breiten beim Walzen: Stahl und Eisen, vol. 45, pp. 190–193.

TRINKS, W. (1915) New theories on hot mill deformations, obtained by experimental rolling: Steel and Iron, vol. 49, pp. 276–277; 422–424; 504–505.

TUTTLE, O. F. (1949) Structural petrology of planes of liquid inclusions: Jour. Geology, vol. 57, pp. 331–356.

WASSERMANN, G. (1939) Texturen metallischer Werkstoffe, Berlin, Julius Springer, 194 pp.

WEISS, L. (1928) Die Fliesslinien des Walzvorganges: Zeitschr. Metallkunde, vol. 20, pp. 302–303.

PHASE RELATIONS OF THE ALKALI FELDSPARS
I. INTRODUCTORY REMARKS[1]

FRITZ LAVES
University of Chicago

ABSTRACT

Monoclinic K-feldspars and triclinic Na-feldspars at high temperatures form a "continuous" series of mix crystals. The apparent lack of a discontinuity in the monoclinic-triclinic solid-solution series has been puzzling. A transition from monoclinic to triclinic symmetry was found to exist and is here described. The composition at which the transition occurs was found to be a function of temperature: $Or_{40}Ab_{60}$ at ~0° C.; Or_5Ab_{95} at ~1,000° C. (extrapolated). The transition considered at a fixed composition as a function of temperature has the characteristics of a *displacive transformation*. The investigation was carried out with natural crystals homogenized at high temperature and quenched. Winchell's term "analbite" is redefined and used for the high-temperature modification of $NaAlSi_2O_8$.

Besides the displacive transformation, another type, or *diffusive transformation*, is considered. A detailed discussion of available data led to the conclusion that the series $KAlSi_2O_8$-$NaAlSi_2O_8$, stable at high temperature (as a sanidine-barbierite, analbite series), differs from those members stable at low temperature (microcline-albite) by a different distribution of the Al and Si ions—disordered at high and ordered at low temperature. A slow and (at least on the potash side) continuous process of ordering in crystals originally disordered is considered to be responsible for the variable appearance of intermediate states (orthoclase, adularia).

The process of K/Na exchange is also discussed in connection with an investigation of different types of perthites, such as those with exsolved albite and those with exsolved analbite.

The meaning of the mineral name "anorthoclase" is considered in connection with some remarks on nomenclature of the alkali feldspars. The extension of this nomenclature to ternary feldspars is illustrated, with some results of an investigation of feldspars from rhombporphyries.

EARLIER PHASE DIAGRAMS

There is a good deal of disagreement and uncertainty in published works on the phase relations in the alkali feldspar systems (cf. Dittler, 1912; Mäkinen, 1917; Mountain, 1925; Winchell, 1925, 1951; Alling, 1926; Vogt, 1926; Spencer, 1937, 1938; Oftedahl, 1948; Bowen and Tuttle, 1950). Most of the disagreement is a consequence of the extreme sluggishness of most of the reactions in this system; in addition, all modern workers have neglected, or have been unaware of, the important observations made in 1883 and 1884 by Förstner, who published on feldspars in the region of $Or_{30}Ab_{70}$. This work will be discussed later in this paper.

Figures 1–5 present a few of the phase diagrams that have been proposed. The main points of difference are as follows: (1) the extent of miscibility between K-feldspar and Na-feldspar at high temperatures; (2) the definition of "anorthoclase" and its relation to the other alkali

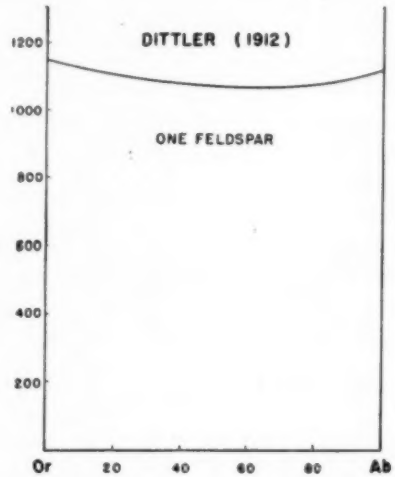


FIG. 1.—Dittler's phase diagram, after Alling (1926).

[1] Manuscript received April 30, 1952.

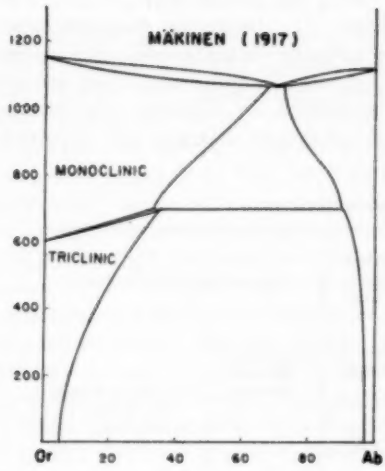


FIG. 2.—Phase diagram after Mäkinen (1917)

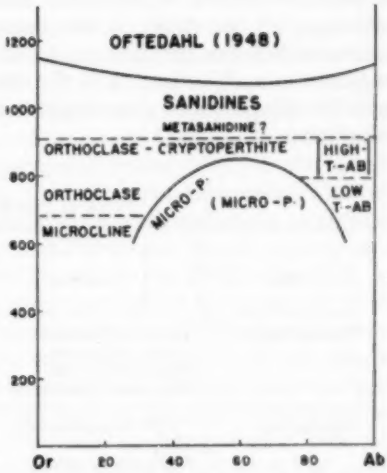


FIG. 3.—Phase diagram after Oftedahl (1948)

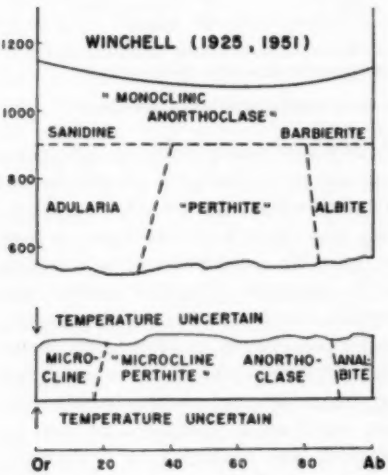


FIG. 4.—Phase diagram after Winchell (1925, 1951).

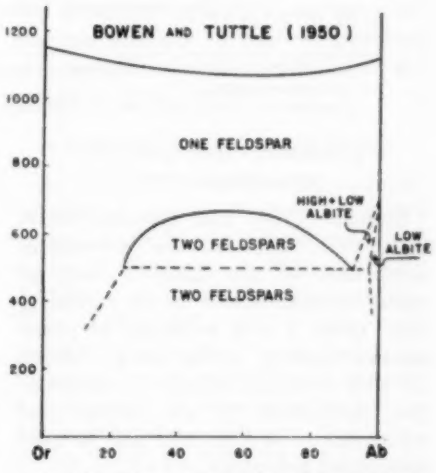


FIG. 5.—Phase diagram after Bowen and Tuttle (1950).

feldspars; (3) polymorphic relations in the pure end-members ($NaAlSi_3O_8$ and $KAlSi_3O_8$); (4) the slopes of the phase boundaries between the high- and low-temperature modifications; and (5) the exsolution temperatures of perthites and antiperthites.

of change. These types can be described by using the terminology of table 1 as follows: (1) *Displacive transformations* are virtually instantaneous and cannot be inhibited by quenching. They are not accompanied by diffusive phenomena, and symmetry changes are involved.

TABLE 1

TYPES OF PHASE TRANSFORMATIONS

Type*	Examples	Transformation Rate	Geometrical Characteristics	
Reconstructive†	Graphite/diamond Calcite/aragonite Quartz/tridymite Tridymite/cristobalite	Slow to rapid	Topological features changed	No change of compositional distribution
Displacive‡	"α/β" transformations High/low quartz High/low tridymite	Rapid	Topological features not changed	
Concealed†	Ferro/paramagnetic iron Rotating/fixed $NaNO_3$	Rapid		
Diffusive	Disordered/ordered Cu_3Au Disordered/ordered CuZn	Slow to rapid		Change of compositional distribution

* Occasionally, combinations of the different types may occur, for example, displacive + diffusive in CuAu.
† After Sosman (1934).
‡ Introduced by Buerger (1948, 1949). It is the same as "alterative" (Sosman, 1934) but is a better term.

A CLASSIFICATION OF PHASE TRANSFORMATIONS

Sosman (1934) and Buerger (1948, 1949, 1951) discussed the geometrical significance of the different kinds of phase transformations in an appealing way. Table 1 is a summary of phase transformations, chiefly after Sosman but with a change (diffusive transformation) introduced by the writer. The nomenclature of this table will be used throughout this paper.

MAIN TYPES OF STATE CHANGES

Experimental observations of the rate of change of one type of feldspar to another, done chiefly with cryptoperthites, indicate the existence of three main types

(2) *Diffusive transformations* are characterized by a change in distribution of Al and Si within the $AlSi_3O_8$ framework. They may (as in K-rich feldspar) or may not (as in Na-rich feldspar) produce symmetry changes. Transformations are sluggish, even near the melting points. (3) In *potash-soda exchange phenomena*, alkali exchange takes place when differing phases (or quasi-phases) in close contact, such as in perthites or cryptoperthites, are subjected to a temperature change. The rate of change in the direction of a new equilibrium state is a function of the temperature and is intermediate with respect to the above two types of transformation. In cryptoperthites it ranges from days at 500° C. to minutes at 1,000° C.

REVIEW OF IDEAS ON THE POLYMORPHISM OF ALKALI FELDSPARS

Numerous earlier writers, on the basis of experimental work with synthetic feldspars (Dittler, 1912; Schairer and Bowen, 1935; Bowen and Tuttle, 1950) and by observation of natural feldspars (Winchell, 1925; Alling, 1926; Vogt, 1926; Oftedahl, 1948), suggested a complete series of solutions between potash and soda feldspar at high temperatures. The inherent difficulty, either neglected or unexplained, in the idea of complete solid solution is the fact that the potash-rich feldspars are monoclinic at high temperatures, whereas the soda-rich feldspars are triclinic. Some writers attempted to overcome this difficulty by use of Mallard's hypothesis that K-feldspar appears to be monoclinic only by virtue of submicroscopic twinning of a truly triclinic material, such as microcline. The ambiguous appearance of the Na-rich members of the alkali feldspar series (called "anorthoclase") was used to support the above view. Several authors considered "anorthoclase" to be a soda-rich microcline (among them Brögger, 1882, 1890, 1897; Alling, 1921, p. 234; Kraus, Hunt, and Ramsdell, 1951; Strunz, 1951). Brögger (1882, pp. 262, 299) introduced the name "soda-microcline." Later Rosenbusch (1885, p. 550) suggested "anorthoclase" as a more appropriate name.

An important approach to the real significance of "anorthoclase" and to its position among the other alkali feldspars was made by Winchell (1925), who collected optical and compositional data from the literature on "anorthoclase." He showed that the optical properties of "anorthoclase" indicate a solid-solution series that, when extrapolated to a pure sodic end-member, results in an albite with optical properties that differ from those of natural albite. On the basis of this extrapolation, Winchell suggested that there might be a modification of albite not described from natural occurrences. He called this modification "analbite." It is of interest to note that these optical properties are virtually the same as those found by Spencer (1937) and Tuttle and Bowen (1950) as characteristic of high-temperature albite. This fact obviously escaped the notice of Spencer, and of Tuttle and Bowen, as well as of the present writer (1950). Winchell did not discuss the stability relations of the "anorthoclase-analbite" series. However (owing to unsatisfactory X-ray data at that time), he erroneously joined Brögger in the opinion that this series is related to microcline, although gaps were observed in the series. Most of the uncertainty on the phase relations of the alkali feldspars as expressed in the different published diagrams seems to have been due to lack of data, first, on the polymorphic relations of the end-members and, second, on misinterpretation of the nature of "anorthoclase."

THE POLYMORPHISM OF $NaAlSi_3O_8$

As indicated by the thermal and optical work of Spencer (1937) and as shown unequivocally by the optical and X-ray work of Tuttle and Bowen (1950), $NaAlSi_3O_8$ exists in two modifications. Both modifications are triclinic, with geometrical relations to each other as described by the writer (1950). At the present time there is no evidence for the existence of other modifications. Tuttle and Bowen (1950, pp. 572–573, 577) discuss this point and specifically exclude the existence of barbierite, a proposed monoclinic modification said to be stable above approximately 900° C. (see discussion in Winchell, 1925, 1951). Tuttle and Bowen (1950, p. 577) quote G. L. Davis as stating that X-ray records of high-tempera-

ture albite made at temperatures up to 1,050° C. show no evidence of an inversion.

For several reasons to be discussed later, the writer prefers to call the modification stable at high temperatures "analbite," a term already introduced by Winchell (1925).

To be able to evaluate fully the phase relations, it is desirable to have some information on the structural differences of the different feldspar modifications. The following data for $NaAlSi_3O_8$ are at hand:

1. The two modifications are triclinic and have the same number of molecules per cell. All cell dimensions are within 1 per cent of one another. The lattice angles differ but slightly: the differences are 50′, 10′, and 2°20′ for α, β, and γ respectively (Laves and Chaisson, 1950).[2] The X-ray intensities of corresponding planes are, on the whole, quite similar.

2. The transformation temperature has been determined by Tuttle and Bowen (1950) as 700° or less. At this temperature the inversion is very sluggish, even under the hydrothermal conditions (plus a sodium silicate flux) under which it was induced. If done dry, the transformation requires very long heating near the melting point, and some albites apparently show little or no tendency to transform in periods of approximately a month or more (see Spencer, 1937; Tuttle and Bowen, 1950).

3. Continuous intermediate states can be observed in the "transformed" material (Laves and Chaisson, 1950).

4. Analbite has never been experimentally transformed to albite; only the reverse has taken place.

These facts strongly favor the conclusion that analbite and albite differ in their distribution of Si and Al ions. There is a widespread opinion in the literature (see, e.g., Buerger, 1948, 1949) that order-disorder transitions require symmetry change and/or a change in the number of molecules per unit cell. This is not necessarily the case, however, and therefore cannot be used as an argument against order-disorder relations in albite. The order-disorder interpretation is not shared by Tuttle and Bowen (1950, p. 580), who write:

> It is concluded that the albite inversion must involve some changes other than Al⇌Si order-disorder. The fact that both modifications are changed by the addition of anorthite in such a manner that they become very similar at An_{35} appears to support the suggestion that Al⇌Si disorder is not the dominant factor in the inversion. Significant differences in refractive indices (density) and the large heat of transformation also suggest marked structural changes.

Inasmuch as the question of the nature of the transition is of considerable importance in the sections to follow, the above view will be discussed in some detail. Tuttle and Bowen's first objection—that both modifications become similar as $CaAl_2Si_2O_8$ goes into solid solution with the $NaAlSi_3O_8$—is considered by the writer to be evidence in favor of a diffusive transformation. Let us consider an albite with an ordered ($AlSi_3$) arrangement. Introduction of anorthite, which has a different Al/Si ratio (Al_2Si_2), necessitates Al-Si disorder in the Si_3 arrangement of albite. Therefore, as anorthite goes into solid solution with albite, the Al-Si arrangement *must* become more disordered in the mix crystal. Obviously, the geometrical differences of the two modifications as expressed by X-ray diffraction records should be smaller as more anorthite goes into solid solution.

The second objection of Tuttle and Bowen to a diffusive transformation—

[2] The value of β for high-temperature albite has not been published previously.

the different refractive indices (density) —is not a valid objection; in fact, it can be considered as being in favor of an order-disorder transformation: Analbite (here suggested as disordered) has N_α, N_β, N_γ = 1.527, 1.532, 1.534, against 1.529, 1.533, and 1.539 for albite (Tuttle and Bowen, 1950, p. 577). Thus analbite should be less dense than albite, and it is generally known that disordered modifications have lower densities than their ordered counterparts (Buerger, 1949).

The third objection is the "large heat of transformation." Again from a structural point of view, a diffusive transformation is favored by this evidence. The heat of transformation, according to Kracek (in Tuttle and Bowen, 1950, p. 581), is approximately 9 cal/gm, as compared to approximately 50 cal/gm (Bowen, 1913) for the heat of melting. Inasmuch as a disordered Al-Si arrangement in crystalline $NaAlSi_3O_8$ resembles the distribution in a glass (liquid) more than that in an ordered crystal, the measured heat of transformation cannot be considered to be too large.

It is, therefore, considered here that albite, stable below approximately 700° C., and analbite, stable above this temperature, represent, respectively, ordered and disordered forms with respect to Al and Si. Further discussion of this point will follow.

ON THE POLYMORPHISM OF $KAlSi_3O_8$ (FIRST CONSIDERATIONS)

So much has been written on the polymorphism of $KAlSi_3O_8$ and so many contradictory opinions have been expressed that no attempt will be made here to summarize this subject. Discussion and references can be found in the papers of Makinen (1917), Alling (1921, 1923, 1926), Winchell (1925), Vogt (1926), and especially Spencer (1937, 1938). More recently, treatments of Oftedahl (1948), Köhler (1949), Laves (1950), and Osten (1951) have appeared.

DATA FROM SPENCER'S INVESTIGATIONS

The mineralogical names generally used for the potash feldspars are sanidine, orthoclase, adularia, and microcline. It has long been known that these "modifications" have different optical properties, which are more or less variable and which show gradual changes that more or less connect several groups with one another. It has also been known that heat treatment may produce significant changes in optical properties. The experiments and discussions of Spencer (1937) shed considerable light on this subject. Some of Spencer's results are summarized here [only his specimens that contain less than 15 per cent (Ab + An) are included, confining the discussion to the potash-rich side of the system; see his samples A, B, C, and U].

1. The unheated "orthoclases" A and C have the "normal" $2V \sim -40°$ with the axial plane in the "normal" position, i.e., parallel to the *b*-axis. Heat treatment at 1,075° C. decreased $2V$, which became 0° after a few hours. Longer heating produced a further change in $2V$, but with the axial plane in the "sanidine" position, i.e., perpendicular to the *b*-axis. Heating for 1 day produced a $2V$ of approximately $-30°$, and in 100 hours the $2V$ of sample A was $-45°$, sample C was $-40°$. An additional 200 hours did not change the specimen by more than 2°, and equilibrium appears to have been reached.

2. The unheated "adularia" B had an original $2V \sim -70°$ in the "normal" position. In 100 hours at 1,075° C. it shrank to approximately $-40°$, and in 300 hours it reached $-15°$, but still in the "normal"

position. The trend of the curve shows that equilibrium was not reached.

3. The unheated microcline U had a $2V \sim -75°$; in 100 hours $2V \sim -45°$. An additional 200 hours took $2V$ through 0°, reaching $-45°$, with the axial plane in the "sanidine" position perpendicular to the *b*-axis. This sample lost its cross-grating twinning and appeared monoclinic.

4. Spencer reported that all heated samples of "orthoclase," adularia, and microcline produce continuous optical changes in the same direction: $2V$ in a plane parallel to the *b*-axis becomes smaller, reaches 0°, and opens again in the plane perpendicular to the *b*-axis until a maximum of 40°–50° is reached. This change is known as "sanidinization."

5. It appears that temperatures near or above 1,000° C. are necessary to produce sanidinization in reasonable laboratory times.

6. There is insufficient evidence to indicate whether or not different equilibrium states of sanidinization exist as a function of temperature (see p. 449).

7. The rate of change differs greatly in different samples having apparently the same composition. This was noted especially in adularias, where even different portions of the same crystal behaved differently. Spencer succeeded in sanidinizing a microcline, whereas others had failed. He also found the same inconsistencies in albite. Amelia County albite changed, upon heating, much more rapidly than an albite from Kodarma. Tuttle and Bowen (1950) reported similar results.

ON ADULARIA

Spencer thus showed that microcline (definitely triclinic) can become optically monoclinic (sanidine) with strong heating. Des Cloizeaux (1876) showed microcline to be triclinic, and Mallard (1876) and Michel-Lévy (1879) proposed and defended the view that the monoclinic optics of orthoclase and sanidine were produced by submicroscopic twinning of microcline. Because of these views, opinions were divided as to whether these three forms were true polymorphs or not. This problem recently was reconsidered by Köhler (1949), who figured microphotographs of adularia showing variations of extinction angle in the same crystal. However, these excellent illustrations do not, in principal, show more than those published earlier by Mallard and by Alling (1921). Köhler concluded that adularia can be triclinic, as did Mallard, but he admitted (1949, p. 55) that his observations do not lead to a definite decision on the presence or absence of polymorphism in $KAlSi_3O_8$.

In textbooks adularia is generally described as monoclinic. It is also generally agreed that adularia is formed at very low temperatures. On the other hand, microcline is considered to be stable at temperatures above those at which adularia is formed. One is then faced with the somewhat puzzling relation of having a "monoclinic" material formed at very low temperatures, a triclinic form (microcline) at intermediate temperatures, and a monoclinic modification again at high temperatures ("orthoclase," sanidine). To avoid this problem, Winchell (1925, 1951) did not distinguish between "adularia" and "orthoclase." In fact, he preferred the term "adularia" and considered orthoclase-adularia to be stable at temperatures below approximately 900° C. He considered microcline to be a separate species having stability relations with respect to orthoclase-adularia "not yet established," and he connected microcline with "anorthoclase" in a microcline-analbite series. Alling (1926, p.

593) criticized Winchell's use of the name "adularia" as "unfortunate in that some adularias are hydrothermal in origin." He neglected adularia and concluded (p. 595): "Our present knowledge seems to be: (1) that above 950°–900° C. sanidine is stable; (2) that between 650°–700° C. and 900° C. orthoclase is stable; (3) that below 650° C. microcline is stable, although Merwin states that 'microcline' appears to be stable to its melting point."

Spencer (1938, pp. 89 ff.) was puzzled by adularia. He presented a qualitative explanation of the sanidine: orthoclase-microcline inversions, assuming a more or less gradual change in optics produced by the effect of temperature on the alkali ions in the $AlSi_3O_8$ framework. He assumed that the range 450°–750° C. "represents the optimum condition for the formation of the microcline form." With respect to adularia, he stated that, for still lower crystallization temperatures in the hydrothermal region, the above influence "would be such that microcline might form, but the necessary disturbing conditions would not usually be present, with the results that the monoclinic form adularia is commonly produced." It is not clear to the writer what "necessary disturbing conditions" may mean.

X-RAY RESULTS

It is desired here to correlate the optical observations on $KAlSi_3O_8$ with X-ray data on K-feldspars now at hand. The writer (1950), observing the optical deviations from monoclinic symmetry in adularia, tried to obtain additional information on Mallard's hypothesis by the application of combined X-ray and optical methods. The same crystal fragments used for optical examination were used for X-ray analysis. The universal-stage optics were done by U. Chaisson (1950). This investigation was carried out in connection with a determination of the microcline lattice, with special reference to its deviation from monoclinic symmetry. Special care was given to the determination of α and γ, which should be 90° if the lattice were "monoclinic," as reported in earlier X-ray investigations (see references in Laves, 1950). Of interest here are the following conclusions (1950, 1951*b*):

1. Microcline[3] has $\alpha = 90°39'$; $\gamma = 87°47'$.

2. Adularia (triclinic)[4] has $\alpha = 90°3'$–$90°8'$; $\gamma = 89°36'$–$89°20'$.

3. Adularia (monoclinic) has $\alpha = 90°$; $\gamma = 90°$.

4. At least three "types" of *optically monoclinic* feldspar exist: (*a*) Truly monoclinic feldspars with sharp diffraction spots and $\alpha = \gamma = 90°$. (*b*) Those which appear optically monoclinic owing to exceedingly fine albite or albite and pericline twinning. In these cases Mallard's view is correct. The tiny triclinic individuals of these crystals have true microcline geometry, as in 1, above. (*c*) Those which appear optically monoclinic but are actually composed of submicroscopic triclinic areas twinned predominantly with the albite law. The triclinic areas, unlike microcline, cannot be characterized by definite values of α and γ. These values deviate from 90°, however, in the same direction as do microcline and adularia. The X-ray diffraction spots of this material are both sharp and diffuse, the difference being a function of the (*hkl*) value of the diffraction spot in reciprocal space.

[3] Average values, crystals from different localities. The writer is aware of the fact that the microclines investigated were undoubtedly not pure $KAlSi_3O_8$. The data here given may be somewhat variable, depending upon Na-content.

[4] Values of samples investigated by the writer. It might not be surprising to find larger or smaller values.

5. Evaluation of the intensities of the X-ray spots indicated that there is a more or less continuous gradation from the truly monoclinic sanidine structure (which can be precisely characterized by X-ray data) to the truly triclinic microcline structure (which can also be precisely characterized by X-ray data). Intermediate members vary more or less continuously with respect to α, γ, and the degree of diffuseness of the X-ray reflections.

6. Additional preliminary experiments have shown that all "normal" orthoclases investigated (using Spencer's term for orthoclases which have a "normal" $2V_a$ of 40°–60° in a plane parallel to the *b*-axis) show characteristic diffuse reflections as illustrated in plate 2, *A* and *B*, of the paper by the writer (1950). A satisfactory explanation has not yet been given for these diffuse reflections, but they can be considered as an indication that these crystals are not in an equilibrium state. This assumption is favored by the fact that heat treatment (sanidinization) weakens and finally eliminates the diffuse reflections. Also, they are not present in microcline.

CONCLUSIONS

The above points 1–6 lead the writer to the following conclusions, which, of course, may be modified as additional data are obtained:

1. There are two stable modifications of $KAlSi_3O_8$. The monoclinic form, sanidine, stable at high temperatures, and the triclinic modification, microcline, stable at low temperatures.

2. The best available evidence, largely from field studies, indicates that microcline is stable below approximately 650°–700° C. (see Makinen, 1917; Alling, 1926, p. 596; Oftedahl, 1948, p. 68).

3. "Normal" orthoclase and adularia (monoclinic or triclinic) are not stable but represent intermediate stages.

STRUCTURAL DIFFERENCES BETWEEN SANIDINE-ANALBITE SERIES AND MICROCLINE-ALBITE SERIES

The following relations should be noted:

1. At high temperatures there is a complete series of solid solutions between sanidine and analbite (Bowen and Tuttle, 1950; Schairer, 1950).

2. Experiments by the writer (1951*a*, *c*) indicated that under special conditions a continuous series of solid solutions between microcline and albite can be produced.

3. The discussion in the preceding section leads to the conclusion that there are only two stable modifications of $KAlSi_3O_8$: sanidine, stable above ~700° C., and microcline, stable below ~700°. Barth's (1934) suggestion that the differences between orthoclase (sanidine) and microcline are due to disordered and ordered Al-Si distributions is adopted here.

4. In the section on the polymorphism of $NaAlSi_3O_8$, two modifications were discussed: analbite, stable above ~700° C., and albite, stable below ~700°. It was suggested that Al-Si order-disorder relations also exist in this pair, analogously with the relations between sanidine and microcline. This hypothesis is strengthened by a comparison of the lattice geometry of the four modifications as given in table 2 (data from Laves, 1951*b*). Note that the "Δ-values" for analbite-albite are of the same magnitude and the same sign as those for sanidine-microcline. The fact that there is no symmetry change in the analbite-albite pair cannot be used as an argument against an order-disorder hypothesis, as mentioned in the discussion of the polymorphism of $NaAlSi_3O_8$. Buerger (1948) sug-

gested order-disorder relations in $NaAlSi_3O_8$ on an intuitive basis and put forth the same relations for anorthite ($CaAl_2Si_2O_8$), in both cases without experimental support. The present writer considers him correct in his views on albite, but recent work (Laves and Goldsmith, 1951, and in preparation) has shown him to be incorrect in the case of anorthite.

phase that may vary structurally, showing states intermediate between those of sanidine and microcline. Different areas of the same crystal may be oriented in a twinlike manner (following pericline and albite laws) with respect to one another. The areas that exhibit "uniform" periodicity range from the submicroscopic to microscopic in size. Different portions of the same crystal commonly

TABLE 2

GEOMETRICAL RELATIONS BETWEEN THE HIGH-TEMPERATURE AND LOW-TEMPERATURE MODIFICATIONS OF K- AND Na-FELDSPARS

	Analbite		Albite	Sanidine		Microcline
α	93°32′		94°20′	90°00′		90°39′
Δ		+48′			+39′	
β	116°30′		116°40′	116°00′		115°56′
γ	89°58′		87°39′	90°00′		87°47′
Δ		−2°19′			−2°13′	
α^*	86°05′		86°20′	90°00′		90°22′
Δ		+15′			+22′	
γ^*	88°17′		90°30′	90°00′		92°10′
Δ		+2°13′			+2°10′	

It is therefore concluded that the sanidine-analbite solid-solution series differs from the microcline-albite series by virtue of a different Al-Si distribution: disordered relations exist in the $AlSi_3O_8$ framework of the high-temperature series; ordered relations in the low-temperature series. This concept easily explains the different types of cryptoperthites, as well as their behavior when heated, as will be seen in the second part of this paper in the section on perthites. The crystallographic difficulty involved in the fact that one end of the sanidine-analbite series is monoclinic, whereas the other is triclinic, will be discussed in the second part in the section on phase relations of this series.

ON THE NATURE AND GENESIS OF ADULARIA

As discussed on pages 442–443, the term "adularia" turns out to apply to a

show different optical properties and show different X-ray diffraction effects.

Adularia is generally considered to have been formed at low temperatures (below approximately 400°; see Spencer, 1938, and other authors) and would, therefore, be expected to exhibit the microcline structure under equilibrium conditions. In view of the consideration that microcline is ordered with respect to Al-Si, it is not unlikely that the rate of growth may be sufficiently high that the ordering forces are overwhelmed during crystallization, producing a more or less disordered (unstable) $AlSi_3O_8$ framework. Being unstable at these low temperatures, the adularia should have a tendency to change continuously to the ordered microcline state. The degree of this change would depend upon the time and temperature relations and on the composition of the crystal, fluxes, etc. The variety of properties observed in

adularia (Köhler, 1949, optical investigation; Chaisson, 1950, universal-stage work; Laves, 1950, X-ray investigation) is easily explained by this hypothesis.

The hypothesis here proposed that $KAlSi_3O_8$ crystallizes "pseudo-stably" or unstably at low temperatures with a (disordered) structure stable at high temperatures has numerous precedents. It is in line with the Gay-Lussac Ostwald step rule of successive reactions (see Hückel, 1951, p. 649). This might be expected to take place especially in systems with diffusive order-disorder relations, the disordered phases tending to appear unstably or "pseudo-stably." In this connection, some remarks of Goldsmith (1949, p. 487) on the metastable formation of carnegieite below its inversion point are here quoted:

> A plausible explanation of this phenomenon from another point of view exists when one considers that the glass represents the most disordered state of the silicate material. The high temperature crystalline phase is most closely akin to the glassy state; in silica glass the random SiO_2 network requires but slight rearrangement or ordering to form cristobalite. The high temperature form might thus be expected to be the one most readily crystallized, even well below its stability range, especially in materials in which ionic movement and rearrangement is inhibited because of high viscosity.

Laboratory crystallization of $KAlSi_3O_8$ produces a high-temperature modification, even when done hydrothermally at low temperatures. All potash feldspars that have been produced by Goldsmith (personal communication) are monoclinic "sanidine," not triclinic microcline, as far as could be determined by the X-ray powder diagrams. The writer knows of no case of a microcline synthesis. This is similar to the proposed unstable (or pseudo-stable) formation of adularia in nature. Analogous results are also obtained in the laboratory synthesis of $NaAlSi_3O_8$. Tuttle and Bowen (1950, p. 573) obtained only analbite, at temperatures down to 250° C.

As already mentioned, the X-ray and optical data on adularia indicate intermediate structural states between sanidine and microcline. On the other hand, no natural albites have been reported that display a behavior that could be considered to be due to an intermediate state between albite and analbite. The low-temperature albites of filled fissures, etc., might, on the basis of this argument, be expected to develop these states. An explanation for this might lie in the fact that both forms of albite are triclinic. A change in the *monoclinic* potash feldspar produces a triclinic modification, and usually does so by twinning. This can be observed optically, as can a small deviation from parallel extinction against (010) cleavage. If, on the other hand, triclinic material (analbite, formed at low temperature) goes through intermediate states to albite, which is also triclinic, there is no reason to do so through the medium of twinning. Also, at no time is parallel extinction involved; therefore, these states, if they exist, might escape observation.

ON THE NATURE AND GENESIS OF "COMMON ORTHOCLASE" AND THE POLYMORPHISM OF POTASH FELDSPARS

The foregoing section treated "adularia" as a more or less independent species of potash feldspar. Most texts treat "adularia" in this fashion, considering it to be a low-temperature form. The writer has adhered to this distinction but is not convinced that such a distinction exists from a structural point of view. No *discontinuity* in properties is apparent; the chief criteria for "adularia" appears to be in occurrence and morphol-

ogy. Some writers, such as Spencer (1938), suggest that below some temperature (approximately 400° C.) adularia is stable. Others, such as Winchell, are not certain that it should be distinguished from orthoclase.

To illustrate this latter point of view, some remarks from Winchell (1951) are here quoted:

In the introduction to the feldspar group it is stated (p. 261): "The chief chemical types are $KAlSi_3O_8$ (orthoclase and microcline), $NaAlSi_3O_8$ (albite) and $CaAl_2Si_2O_8$ (anorthite). Natural crystals of orthoclase and of microcline usually contain 10 to 25 percent $NaAlSi_3O_8$." On page 263: "Or" is used as an abbreviation for the "orthoclase molecule." On page 265, in a table on "Crystallography of the Feldspars," the name "orthoclase" does not appear at all, only adularia, sanidine, and microcline are included. On page 275, in a table of optic angles, the names "orthoclase (adularia)," sanidine, and microcline are used. In a table of optics on page 276, only orthoclase and microcline appear. On the same page, with respect to inversions, it is stated: "Potash feldspar, $KAlSi_3O_8$, exists in nature in three crystal phases: the triclinic phase is called microcline; the two monoclinic phases are both known as orthoclase. The low-temperature phase of orthoclase, called adularia, inverts at about 900° C. to the high temperature form, called sanidine." In a chapter on classification it is stated (p. 297): "Ordinary orthoclase of plutonic rocks has properties which differ a little from those of adularia, but perhaps these two are one phase. This low-temperature phase differs notably from the high-temperature phase, called sanidine, though both are monoclinic." In the following pages (297–301) dealing with the $KAlSi_3O_8$-$NaAlSi_3O_8$ mix-crystal series, the name "orthoclase" does not appear at all. Only the properties of sanidine, adularia, and microcline are discussed. In a classification of the feldspars as to symmetry, the groups "orthoclase (adularia)," "sanidine," and "microcline" appear again, and the same grouping is used for the detailed description. In the section on the detailed description of "orthoclase (adularia)" (pp. 303–305), the term "orthoclase" is used throughout, with one exception when he states: "Optic angle large—usually about 50° to 70° in 'adularia' and 60° to 85° in orthoclase." In addition to the fact that the ranges overlap, this statement is opposed to the general remarks on optic angles on page 275.

The above-quoted inconsistencies are illustrative of the state of published knowledge. They are presented here not as criticism but as an indication of the impossibility of obtaining an integrated picture of the potash feldspars from the literature. The reported inconsistencies may be avoided by the following assumptions:

1. Potash feldspar, $KAlSi_3O_8$, is dimorphic, having two *stable* modifications. These are (see section on polymorphism of $KAlSi_3O_8$) *sanidine*, stable above approximately 700° C., and *microcline*, stable below this temperature.

2. In sanidine, Al and Si are disordered (see Barth, 1934; Cole, Sörum, and Kennard, 1949); in microcline Al and Si are ordered (see point 8 below).

3. Many investigations have been concerned with the subject of order-disorder transformations, which are usually "second-order transitions" (see, e.g., Cowley, 1950, on Cu_3Au). The "ordered" modification is never ideally or completely ordered, the degree of order being a function of temperature. In the case of the potash feldspars it can be assumed that, just above the inversion

temperature (arbitrarily taken here as ~700° for purposes of discussion), rather complete disorder exists (at least as far as the "long-range" relations are concerned), the symmetry being monoclinic. Below ~700° C. some ordering tends to develop, with a more or less continuous change in α and γ. These values increasingly deviate from 90° with the increase in order as a function of temperature; at approximately 600° C. (rough estimate) a high degree of order may be reached, with α and γ characteristic of the microcline structure as found in nature.

4. It follows that a continuous sequence of potash feldspars, showing variations in order as a function of temperature, may exist under equilibrium conditions somewhat below the transformation temperature.

5. Adularia is formed at temperatures far below the order-disorder transformation temperature. It may thus crystallize as a completely disordered (monoclinic) or highly disordered (somewhat triclinic) form. It may also be possible that under special conditions the highly ordered microcline is formed. From this viewpoint, adularia is *not* a distinct modification of $KAlSi_3O_8$. Aside from its morphology, one of the chief characteristics of adularia is its variability as expressed in optical properties, the variation being induced by environmental differences during and after crystallization. The rate of crystallization might strongly influence the degree of disorder, as might the length of its whole thermal history.

6. In similar fashion *orthoclase*, or rather *common orthoclase* (a name here to be used), is believed to be unstable. Common orthoclase may have formed either above ~700° C. as a stable disordered monoclinic modification or also as a monoclinic modification below the transformation temperature under nonequilibrium conditions. The large temperature range and variation of environment in which common orthoclase may form probably accounts for the habit variations observed, whereas the limited environmental conditions under which adularia forms probably account for its more distinctive morphology. A disordered monoclinic orthoclase, formed either metastably below ~700° or stably above this temperature but then cooled below ~700° C., tends to go in the direction of the stable microcline. The degree of conversion to microcline is again dependent upon environmental conditions, chiefly time and temperature. It is thus not surprising to find in natural crystals a variety of intermediate states expressed by variable optical properties (for example, $2V$) and variable degree of diffusion in the X-ray diffraction photographs.

7. The optical behavior of $KAlSi_3O_8$ crystals heated in the laboratory (see Spencer, 1937) is in general agreement with the picture presented above (1–6). There are, however, a few of Spencer's observations that may indicate that the present interpretation has to be modified. This modified picture will be discussed below (8). These divergent observations, made with his specimens A (95 per cent Or) and C (92 per cent Or) are: (*a*) Heating at 1,075° for 100 hours produced values of $2V$ [in the sanidine position, parallel (010)] of 53° and 45°; an additional 200 hours produced no further effect. On reheating to 1,120° for 12–14 hours, however, the $2V$ values changed a bit more, to 58° and 53°, respectively. (*b*) In specimen A, a 50-hour heating at 1,100° C. gave a $2V$ of 54°, and a slow cooling (70 hours) from 1,100° to 770° "changed" $2V$ to 53°. (*c*) Specimen A was again heated (150 hours) at 900°, and $2V$ was found to be 44°. (*d*) Spencer states (1937, p. 477): "These results suggest

that slow cooling may to some extent reverse the direction of change of optic axial angle, particularly in the region of 1,000–900° C., but they are not conclusive. In any case the changes are sluggish."

Observation *c* is evidence against the picture here presented (1–6). If statement 1 is correct, heat treatment of a $KAlSi_3O_8$ crystal at temperatures above ~700° C. would tend to change its properties in the direction of sanidine. This direction, as shown by Spencer, is an enlargement of $2V$ in (010). Therefore, a specimen that had reached $2V = 53°$ should not go back to $2V = 44°$ when heated at 900°. Assuming Spencer's observation to be typical, we must conclude that the interpretation in statements 1–6 must be amended. This can be done quite easily on an order-disorder basis, as follows:

8. In an earlier paper the writer (1950) showed, by means of a systematized application of Barth's (1934) order-disorder hypothesis on potash feldspars, that there are six principal arrangements of Al and Si in a sequence from complete disorder to complete order in the potash feldspar structures. Two of these arrangements have monoclinic symmetry, and four have triclinic symmetry. Thus there are two arrangements of Al and Si available for a truly monoclinic feldspar (listed as 1 and 2 in table 1, Laves, 1950, p. 549). These are distinguished by the following characteristics: The base-centered cell of potash feldspar contains four molecules (Taylor, 1933; Taylor, Darbyshire, and Strunz, 1934). The 4 Al and 12 Si = 16 atoms are distributed on two equivalent point groups, each consisting of 8 points. One of the arrangements is completely disordered, with the distribution (2 Al + 6 Si) + (2 Al + 6 Si); the other arrangement is partially ordered, with a distribution of (4 Al + 4 Si) + (8 Si). A continuous sequence between these two limiting monoclinic cases is theoretically possible.

Thus two different "sanidine" arrangements are possible from a structural point of view and could be distinguished as "sanidine (high)" and "sanidine (low)." The relation of this consideration to the "high sanidine" as opposed to "sanidine" mentioned by Tuttle and Bowen (1951) in an orally presented paper on "The Four Series of Alkali Feldspars" is yet unknown.

REFERENCES CITED

Alling, H. L. (1921) The mineralogy of the feldspars. Part 1: Jour. Geology, vol. 29, pp. 193–294.

——— (1923) The mineralogy of the feldspars. Part 2: *ibid.*, vol. 31, pp. 282–375.

——— (1926) The potash-soda feldspars: *ibid.*, vol. 34, pp. 591–611.

Barth, T. F. W. (1934) Polymorphic phenomena and crystal structure: Am. Jour. Sci., vol. 27, pp. 273–286.

Bowen, N. L. (1913) The melting phenomena of the plagioclase feldspars: Am. Jour. Sci., vol. 35, pp. 577–599.

——— and Tuttle, O. F. (1950) The system $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O: Jour. Geology, vol. 58, pp. 484–511.

Brögger, W. C. (1882) Die silurischen Etagen 2 und 3 im Kristiania—Gebiet und auf Eker; Universitätsprogramm für 2 Sem. 1882, Kristiania, 376 pp.

——— (1890) Die Mineralien der Syenitpegmatitgänge der südnorwegischen Augit- und Nephelinsyenite, 2 Teil: Zeitschr. Kristallographie, vol. 16, pp. 5–658.

——— (1897) Die Ganggefolge des Laurdalits (die Eruptivgesteine des Kristianiagebietes III): Vidensk. selsk. Skr., I. Math.-naturv. Kl., no. 6, 377 pp.

Buerger, M. J. (1948) The role of temperature in mineralogy: Am. Mineralogist, vol. 33, pp. 101–121.

——— (1949) Disorder in crystals of non-metals: Anais Acad. Brasileira de Cien., vol. 21, pp. 245–266.

——— (1951) Crystallographic aspects of phase transformations; in: Phase transformations in solids. Symposium held at Cornell University, 1948, New York, John Wiley & Sons, Inc., pp. 183–212.

CHAISSON, U. (1950) The optics of triclinic adularia: Jour. Geology, vol. 58, pp. 537–547.

COLE, W. F.; SÖRUM, H., and KENNARD, O. (1949) The crystal structures of orthoclase and sanidinized orthoclase: Acta Crystallographia, vol. 2, pp. 280–287.

COWLEY, J. M. (1950) X-ray measurements of order in single crystals of Cu_3Au: Jour. Applied Physics, vol. 21, pp. 24–30.

DES CLOIZEAUX, L. (1876) Mém. sur l'existence, les propriétés optiques et cristallographiques, et la composition chimique du microcline, nouvelle espèce de feldspath tricliniques à base de potasse, suivi de remarques sur l'examen microscopique de l'orthose et des divers feldspaths tricliniques: Annales chim. physique, vol. 9, pp. 433 ff.

DITTLER, E. (1912) Die Schmelzpunktkurve von Kaliumnatronfeldspäten: Tscherm. Mitt., vol. 31, pp. 513–522.

FÖRSTNER, H. (1883) Ueber die Feldspäthe von Pantelleria. Zeitschr. Kristallographie, vol. 8, pp. 125–202.

——— (1884) Ueber künstliche physikalische Veränderungen der Feldspäthe von Pantelleria: *ibid.*, vol. 9, pp. 333–352.

GOLDSMITH, J. R. (1949) Some aspects of the system $NaAlSiO_4$-CaO-Al_2O_3: Jour. Geology, vol. 59, pp. 19–31.

HÜCKEL, W. (1951) Structural chemistry of inorganic compounds, New York, Elsevier Publishing Co.

KÖHLER, A. (1949) Zur Optik des Adulars: Neues Jahrb. 1945–1948, Abt. A, Monatsh., Stuttgart, pp. 49–55.

KRAUS, E. H.; HUNT, W. F.; and RAMSDELL, L. S. (1951) Mineralogy, 4th ed., New York, McGraw-Hill Book Co., Inc.

LAVES, F. (1950) The lattice and twinning of microcline and other potash feldspars: Jour. Geology, vol. 58, pp. 548–571.

——— (1951*a*) Relationships between exsolved plagioclase and its host (abstr.): Meeting Am. Cryst. Assoc. Proc., Washington, February, 1951, p. 33.

——— (1951*b*) A revised orientation of microcline and its geometrical relation to albite and cryptoperthites: Jour. Geology, vol. 59, pp. 510–511.

——— (1951*c*) Artificial preparation of microcline: *ibid.*, pp. 511–512.

——— and CHAISSON, U. (1950) An X-ray investigation of the high-low albite relations: Jour. Geology, vol. 58, pp. 584–592.

——— and GOLDSMITH, J. R. (1951) On the superstructure in anorthite (abstr.): Meeting Mineralog. Soc. Proc., Detroit, November, 1951.

MÄKINEN, E. (1917) Ueber die Alkalifeldspäthe: Geol. fören. Förh., vol. 39, pp. 121–184.

MALLARD, F. (1876) Explications des phénomènes optiques anomaux, qui présentent un grand nombre de substances cristallisées: Annales des mines, vol. 10, pp. 157 ff.

MICHEL-LÉVY, M. (1879) Identité probable du microcline et de l'orthose: Soc. min. France Bull. 5., pp. 135–139.

MOUNTAIN, E. D. (1925) Potash-oligoclase from Mount Erebus, Antarctica, and anorthoclase from Mt. Kenya, East Africa: Min. Mag., vol. 20, pp. 331–345.

OFTEDAHL, C. (1948) Studies on the igneous rock complex of the Oslo region. IX. The feldspars: Norske vidensk. Akad. Oslo Skr., I. Mat.-naturv. Kl., no. 3, pp. 1–77.

OSTEN, J. F. (1951) Identificatie van natuurlijke alkali-veldspaten met behulp von Röntgenpoederdiagrammen: Leidse Geol. Meded., vol. 17, pp. 1–69.

ROSENBUSCH, H. (1885) Mikroskopische Physiographie der Mineralien und Gesteine. Vol. 1, Die petrographisch wichtigen Mineralien, 2d ed., Stuttgart, Schweizerbarth.

SCHAIRER, J. F. (1950) The system $NaAlSiO_4$-$KAlSiO_4$-SiO_2: Jour. Geology, vol. 58, pp. 512–517.

——— and BOWEN, N. L. (1935) Preliminary report on equilibrium relations between feldspathoids, alkali-feldspars, and silica: Am. Geophys. Union Trans., 16th Ann. Meeting, pp. 325–328.

SOSMAN, R. B. (1934) Change of phase and change of constitution in the solid state: Ceramics Conf. Proc. Bull. 14, pp. 11–27.

SPENCER, E. (1937) The potash-soda feldspars. I. Thermal stability: Min. Mag., vol. 24, pp. 453–494.

——— (1938) The potash-soda feldspars. II. Some applications to petrogenesis: *ibid.*, vol. 25, pp. 87–118.

STRUNZ, H. (1949) Mineralogische Tabellen, 2d ed., Leipzig, Akadem. Verlagsgesellschaft.

TAYLOR, W. H. (1933) The structure of sanidine and other feldspars: Zeitschr. Kristallographie, vol. 85, pp. 425–442.

———; DARBYSHIRE, J. A.; and STRUNZ, H. (1934) An X-ray investigation of feldspars: Zeitschr. Kristallographie, vol. 87, pp. 464–498.

TUTTLE, O. F., and BOWEN, N. L. (1950) High temperature albite and contiguous feldspars: Jour. Geology, vol. 58, pp. 572–583.

——— — ——— (1951) Four series of alkali-feldspars (abstr.): Meeting Min. Soc. Proc., Detroit, November, 1951.

VOGT, J. H. L. (1926) The physical chemistry of the magmatic differentiation of igneous rocks. II. On the feldspar diagram Or-Ab-An: Norske vidensk. Akad. Oslo Skr., I. Mat.-naturv. Kl., no. 4, pp. 1–101.

WINCHELL, A. N. (1925) Studies in the feldspar group: Jour. Geology, vol. 33, pp. 714–727.

——— (1951) Elements of optical mineralogy. Pt. 2: Description of minerals, 4th ed., New York, John Wiley & Sons, Inc.

[Part II of this paper will appear in the following issue of the *Journal*.]

SELENOMORPHOLOGY[1]

ALICE COLEMAN
University of London

ABSTRACT

This paper is an attempt to apply the systematic principles of geomorphology to an analysis of the land forms of the moon. A comparative approach, based on desert morphology, has both potentialities and limitations. A deductive approach, in terms of structure, process, and stage, is considered more fruitful. In the absence of air and moisture on the moon, the dominant processes at work are slow mechanical disintegration of rock material and its transportation and deposition under gravity. The term "graviplanation" has been introduced. An early stage is the formation of scree at a generally higher angle of rest than on earth, owing to lower values of lunar gravity. Further comminution leads to the creation of flat "graviplanes," each crater acting as a local base level. Protracted transfer of material from higher to lower graviplanes would eventually make the lunar surface entirely smooth.

The progress of this cycle is inevitably delayed by meteorite impacts, which re-create relief. While any part of the initial cooling surface remains, differentiation is bound to continue. This is the stage of youth, exhibited by the maria. Maturity follows when the whole surface is crater-scarred, as in the uplands; thereafter, the meteorites strike weakened, instead of compacted, rock, and their powers of creating relief begin to diminish. The proved decrease in their numbers through lunar history accentuates this tendency. The denudational processes gradually become relatively more efficacious.

The graviplanation cycle can never have been rejuvenated by marine transgressions. Therefore, apart from lava flows, the moon's surface is entirely the work of a single, barely mature cycle. The extreme slowness of lunar change in comparison with that of the earth cannot be overemphasized.

INTRODUCTION

Imagine a land mass on which no rain falls, no rivers flow, no glaciers form, no waves beat, no winds blow. Let chemical and mechanical disintegration disrupt the rocks and gravity exert its downward pull. On such a land mass, earth and rock will ceaselessly move from higher to lower levels, slopes will soften, relief will fade. Given time enough, the whole will be reduced to a featureless plain of disintegrated rock debris . . . (D. W. Johnson, in Sharpe, 1938, preface).

Such a land mass exists on this earth only in the imagination, but the moon comes very near to providing it. The land forms of the moon are full of interest for the geomorphologist, as the interaction of morphological processes is quite different from that of earth. Certain processes which are dominant here are entirely absent there, whereas others which are found here only in subsidiary roles, stand in isolation and supremacy there. It is hardly permissible to use the term "*geo*morphology" for extra-terrestrial studies: nor does the well-established "selenography" quite suit the case, as it deals with the distribution of lunar land forms rather than with their dynamic evolution. However, "selenomorphology" (Greek σεληνη, "moon," μορφη, "form," λογος, "a discourse") is a perfectly clear and apt term and has been adopted here.

Selenomorphology may be approached in three ways, by observation, by geographical comparison, and by deductive reasoning.

OBSERVATIONAL APPROACH

The first approach is the province of selenography and is well documented. Modern telescopes have effectively brought the moon to within a range of 200 miles as it would be seen by the naked eye. Beautiful lunar photographs have been studied with increasing precision, and detailed maps and atlases have been compiled. Craters, mountains, plains, and other features have been named, and their distribution upon the earthward face of the satellite is fully

[1] Manuscript received August 13, 1951.

known (fig. 1). Beyond this descriptive work there have been both generalized explanations of the moon's bare, rugged, desert-like appearance and detailed and interesting reflections upon the origin of certain puzzling features. But there does not appear to be, as yet, any systematic attempt to apply the principles of earth sculpture to moon sculpture.

COMPARATIVE APPROACH

The moon's face cannot be explored at first hand, but that of the earth is readily accessible, and this permits certain comparisons to be instituted. The closest terrestrial counterparts of lunar landscapes are the rock deserts of the tropics. Any ordered sequence of changes noted in the course of a traverse from the wetter periphery to the drier interior of these deserts might well point the way, by extrapolation of the trend, to more extreme forms characterizing the moon. One feature, the alluvial fan, may be taken as an example. Fans denote the concentration of running water in

FIG. 1.—Key map to show the position of features mentioned in the text

streams at particular points and may well show gradation in form, as rainfall decreases. Outside the desert margins, fans would be large, with a gentle angle of rest, because there is both adequate river transport to bring down plenty of detritus and adequate rainwash to sift out a toe slope. In an inner zone the fans may be characteristically steeper, as there would be occasional strong flood transport to deposit the material, but less rainwash to lower it. Toward the center the fans may become lower and smaller, because the intermittent streams are shorter-lived and cannot build such large cones, whereas there are longer periods of eolian and gravitational reduction between the showers. Still drier conditions where streams are entirely absent would not see the concentration of detritus into fans at all. Instead, there would be continuous screes of roughly constant dimensions fringing all the slopes. This last type of formation must necessarily prevail upon the riverless moon. It is a small defect in Chesley Bonestell's otherwise admirable portrayal of lunar landscapes (1950) that he does include individual talus cones.

The example given is hypothetical but highly suggestive of potentialities. If a number of such radially inward gradations could be formulated on the basis of actual observations, they would be both interesting in themselves and germane to selenomorphology. It is not impossible that this latter study might, in turn, contribute something to the understanding of arid processes. For example, the steep slopes of the moon resemble those of the terrestrial deserts, but they cannot be the work of either eolian abrasion, lateral corrasion, or sheet-flood erosion, the three main processes at present invoked by geomorphologists to explain our arid landscapes.

It would no doubt be instructive to go beyond the well-charted deserts to the world's most arid area, the Atacama, of which there is practically no mention in morphological literature. As an area where rain has not been known to fall, it may well hold the key to a number of desert problems, and it is perhaps more like the moon than any other part of the earth. Even so, it still differs from the moon as a landscape-making environment in several important respects. These may be enumerated, in order to emphasize the caution with which the comparative method should be applied.

First, although no rain has been recorded, the Atacama may have been wetter in quite recent times and may owe much to the processes of normal erosion. Second, dew and mist are characteristic and support a sparse vegetation which binds the soil and fosters chemical decomposition. And, third, wind transport and the other effects of an atmosphere still distinguish the area from the airless satellite. In all these respects the Atacama and the moon are not comparable, and, in the final analysis, the gulf between them must still be spanned by deductive reasoning.

THE DEDUCTIVE APPROACH

W. M. Davis' deductive systematization of the study of land forms has been the prime inspiration of the science of geomorphology. With lucid exposition he showed how the varied processes which are currently at work upon existing rocks and crustal structures must inevitably lead through an ordered development of sequential forms to an end-product, or peneplane. Thus he provided an illuminating frame of reference which has proved itself sufficiently broadly based to contain also the effects of tectonic, eustatic, and climatic interruption. A deductive approach to selenomorphology cannot do better than to apply this same

frame of reference to the evolution of lunar landscapes. It is therefore logical to consider the efficacy upon the moon of process, structure, and stage.

PROCESS

For the present purpose the processes operative upon the earth may be divided into five groups: (1) the work of water in erosion, transportation, and deposition by rain, rivers, glaciers, and the sea; (2) erosion, transportation, and deposition by the wind; (3) chemical and mechanical weathering; (4) transportation and deposition by gravity; and (5) tectonic activity. This last embraces the structure-forming processes and will receive separate attention.

The first and second of these groups must be considered inoperative upon the moon, since there is no lunar atmosphere or hydrosphere. This is the result of the low value of gravity at the moon's surface, which fixes the velocity of escape at 1.47 miles/sec. Though this is a higher figure than the *mean* molecular velocity of atmospheric gases and water vapor at 100° C., individual particles can temporarily exceed it and so break free of the moon's gravitational field and escape into outer space. The moon has, in fact, been powerless to hold an atmosphere and is now entirely dry and entirely airless.[2] This has a profoundly limiting effect upon the range of morphological processes. No wind or water erosion is possible.

Of the third group, chemical weathering must be dismissed because neither hydration nor oxidation is possible. Carbonation, too, requires water, and reduction has probably long since reached a stable maximum. But mechanical weathering, on the other hand, must be extremely important, as judged by earth standards. During the long lunar day, which is equivalent to fourteen of ours, the sun's rays stream in at full strength. There is no atmospheric absorption, and temperatures rise to a very high figure, variously estimated between 214° and 350° F. Conversely, there is no atmospheric delay in night radiation, and temperatures fall to −250° F. or lower. Even more striking than this enormous diurnal range is the rapid fall of temperature recorded during a lunar eclipse, 170° in an hour. Such rapid cooling could occur only in rocks which are very poor conductors of heat. The maximum expansion and contraction occurring in the surface rock must fall off very sharply with depth, and so cause flaking and exfoliation, even though the diurnal changes are relatively slow. After a time, however, certain parts of the surface would be protected by the accumulation of comminuted fragments, which would decrease the efficacy of the process. It should also be noted that the freeze-thaw mechanism, which is important on the earth when the temperatures oscillate about 32° F., can play no part in lunar disaggregation. This figure is not selenomorphologically significant. In spite of these limitations, however, slow exfoliation and allied processes must remain the dominant form of erosion upon the surface of the moon.

The fourth group of processes is also highly important. Though the moon's gravitational force is lower than the earth's, its morphological influence is vastly greater, as it appears to be almost the sole agent of transport and deposition. The range of lunar-mass movements is narrow. There can be no downhill flow which involves lubrication of the rock by ice or water, and the horizontal

[2] The absence of absorption and refraction effects shows that any lunar atmosphere must be at least one hundred thousand times more tenuous than that of the earth. It could have no morphological influence.

component in the translocation must be very restricted. Conditions come as near as may be envisaged to "equiplanation" as conceived by D. D. Cairnes (1912). He defines its action as including "all physiographic processes which tend to reduce the relief of a region, and to cause the topography to become more and more plainlike in contour, without involving any loss or gain of material to the area affected." However, Cairnes's concept embraces processes which are not operative on the moon, and regional loss and gain would be expected in the late stages of lunar evolution. Hence the term "equiplanation" is not employed here, but the self-explanatory "graviplanation" is substituted.

Thus is produced a picture of selenomorphological processes in which mechanical weathering is responsible for disaggregation, and gravity for transport and deposition. It is now necessary to consider the type of surface upon which these processes are at work.

LITHOLOGY AND STRUCTURE

Observational data which illuminate the constitution of the moon's crust include the figure for the "albedo," or brightness, which depends on the proportion of received sunlight which the moon reflects. This figure is low, only 7 per cent, and this indicates that the surface rocks are dark in color, like slate or basic lava, and probably brown rather than gray. Polarization curves produced by the moon are similar to those produced by a mixture of brown and gray volcanic ash. The reflected light also suggests that the comminuted fragments are coarse, inasmuch as fine dust is an excellent reflector.

Further information may be formulated deductively. The dissipation of the moon's atmosphere is believed by Jeans to have been completed within a few thousand years after the birth of the satellite. Consequently, there can have been no sedimentation (or at the most the merest trace), and sandstones, limestones, clays, and shales must be entirely foreign to lunar lithology. Though material is constantly undergoing mechanical disaggregation, the absence of water grading and wind sifting means that fragments of all types and caliber accumulate together, completely unsorted. It is difficult to conceive of any process by which this gravel or dust can be consolidated: once formed, it doubtless remains as loose material undergoing progressive comminution.

There is clearly a profound cleavage in character between the dusty weathering product and the rugged walls and ridges from which it is won. As with the earth, the original rocks of the moon are believed to have been crystalline, and, in the absence of sedimentation and resorting, so they must remain. They are probably traversed by joints and veins which affect the pattern and texture of exfoliation and maintain the rugged nature of the rock faces.

The influence of crustal movement upon such a surface must be carefully examined. On the earth such movements take three main forms: folding, faulting, and igneous activity. Folding implies a certain plasticity of the crust, whereas fracturing characterizes more rigid terrain. Although, no doubt, folding was possible when the internal temperature of the moon was higher than it is now, there is no positive evidence of folded structures. Conspicuous mountain arcs certainly exist, but they are explicable in other terms. At present the crust seems to have lost the resilience necessary for buckling and warping movements. This appears to be largely due to the gradual

cooling of the satellite, but a contributory factor may have been the loss of moisture and fluid materials from the crust. Moreover, in the absence of transfer of detritus from one part of the crust to another, there is no true geosynclinal accumulation and hence no sedimentation-subsidence or related isostatic movements.

It seems reasonable, therefore, that any tectonic activity now current in the cold, desiccated, and rigid lunar shell should express itself in faults rather than in folds. There is, in fact, ample evidence of fracturing. One of the five major types of lunar feature is the *rill*. Rills appear to be wide, gaping cracks or fissures up to a mile across (pl. 1, *A*). They occur around the edges of the lowland plains or maria (singular, "mare") and traverse the mountains without regard for topography. They are generally curved in plan and do not have tributaries. All these characteristics suggest that they are tensional faults which have not been infilled with dike material, except locally. A more individualized faulted feature is the Straight Wall, situated near the crater Tycho. It forms a bright line when the sun shines on it and casts a shadow when the sun is behind it. This shadow can be seen in plate 1, *A*, and measurement of its breadth reveals that the Straight Wall is a cliffed scarp up to 1,500 or 2,000 feet in height.

It was formerly believed that the lunar craters were extinct volcanoes, but this view has been superseded by the theory of meteorite impacts, which has received very full treatment from the pen of R. B. Baldwin (1949).

Lunar craters differ from terrestrial volcanoes in a number of ways. With few exceptions, they are not associated with lava flows, and they are also commonly too large (Clavius, the greatest, is 156 miles in diameter) to be plausibly attributed to any known volcanic process. Moreover, they are not aligned along zones of crustal weakness but are distributed in a perfectly random scatter.

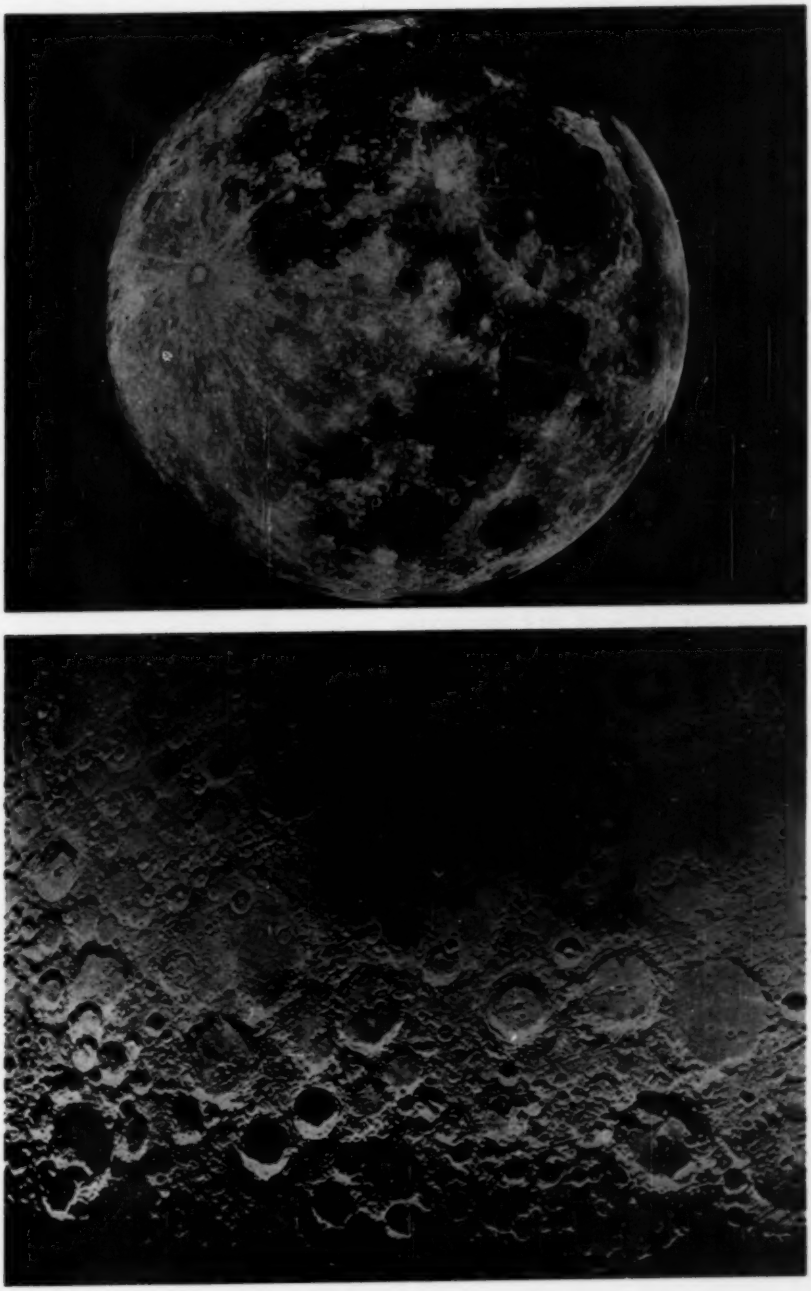
Conversely, they display several points of affinity with impact craters. The material which forms the ringwall is of approximately the same volume as the central cavity, suggesting that it has been raised up out of the center, partly by outward compression and partly as explosion ejectamenta which now litter the outer slopes in a brecciated state. Baldwin has strengthened this argument by a comparative analysis of the form and proportions of some fifty terrestrial meteorite craters and numerous shell holes, bomb craters, and explosion pits. All these show a regular change in their proportions with increase in size, and an extrapolation of the trend coincides very closely with figures derived from fresh-looking craters of the moon.

Baldwin has also used the meteorite hypothesis in explaining other lunar land forms. For example, the central peaks, which were long a puzzling feature of certain craters, proved to be quite commonly represented in bomb craters also. They

PLATE 1

A, Part of the Mare Nubium, bordered by crater topography (Mount Wilson). The Straight Wall appears as a white line in the center of the photograph and is approximately paralleled by a short arcuate rill on the right. Courtesy Mount Wilson and Palomar Observatories.

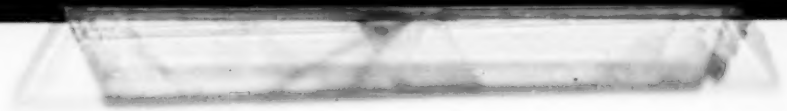
B, The full moon (Chappel, Lick). Note the maria, or smooth dark areas, and the bright ray systems, of which that centered on Tycho, near the South Pole, is the most conspicuous. (South is shown at the top of these photographs.) Courtesy Lick Observatory.



B

A

Lunar features



lie well below the level of the undisturbed ground outside and appear to be that material which is not fully blasted out by the explosion. The material which *is* flung out falls in a radial scatter to form the impressive light-colored rays which center on certain craters and ignore all other topographic forms. Its pulverized state would account for its high powers of reflection. A fine example is the ray system centered on Tycho (pl. 1, *B*). The valleys of the moon bear a similar radial relationship to certain craters and maria and are regarded as grooves gouged out by flying material ejected at low angles from the sites of the most violent impacts. Some of them are of immense size, for example, the Great Valley of the Lunar Alps, which is 83 miles long and up to 6 miles wide.

Because the meteorite hypothesis is adequate to explain practically all lunar land forms and their mutual relationships, only a very minor role can have been played by spontaneous igneous activity. Nevertheless, extensive lava plains exist on the moon. These are the maria, or smooth, dark areas, conspicuous in plate 1. They are by far the largest features of the moon and are encircled by the most impressive of the mountain arcs, up to 26,000 feet in height. They appear to be the ruins of former gigantic craters. The lavas are traversed by sinuous ridges resembling flow structures, and their marginal rills, mentioned above, are also consistent with a history of cooling from a molten state. The maria are believed to have originated when two particularly powerful meteorites broke through the crust. After violent ejection of the material which scored the valleys, they permitted an upsurge of magma from the interior. Three contemporary lava flows spread widely over the face of the moon. Hence even the igneous tracts are primarily attributable to the same mechanism as the other land forms.

The frequency of lunar impacts in comparison with those of the earth has a double explanation. First, the earth's atmosphere burns up many of the meteorites passing through it and converts the majority of them to dust before they reach the ground. The moon has no such protective atmosphere. Second, erosion can speedily efface terrestrial craters, whereas those of the moon are attacked more slowly and can be preserved through long geological periods. Craters are thus an expectable feature of the lunar surface: their absence would be anomalous.

STAGE

The question of selenomorphological stage will be approached in two ways. It is proposed, first, to outline an ideal cycle of graviplanation and note its intimate interaction with processes which differentiate the landscape. This will be followed by a brief study of individual land forms as the basis of an actual denudation chronology.

Because we have to deal with the operation of a limited number of processes upon a limited variety of structures and types of rock, the deduction of a lunar cycle of erosion should be a relatively simple matter. Once the cycle has been initiated, it is plain to see how simply and surely graviplanation will reduce the whole lunar surface to a featureless expanse. Individual slopes may be subjected to the method of slope analysis employed by A. Wood (1942) for humid temperate regions. In spite of the great climatic difference involved, the early stages of Wood's slope cycle appear to be valid for the moon.

The "free faces" of the moon weather

back parallel to themselves, in so far as they are not differentially protected from temperature contrasts by permanent shadows and as long as a change of slope is not induced by the control of joints and veins. At the foot of each free face screes accumulate, and, as previously argued, these must be roughly constant in size all along their length, as there are no streams to concentrate material into fans or cones. The angle at which these scree slopes stand depends upon the size of the fragments, as larger blocks are stable at higher angles of rest than smaller ones. In general, the limiting angles of rest must be greater than for material of corresponding caliber on the earth, as the pull of gravity is only one-sixth as great. Steep slopes, therefore, must be characteristic. It has been calculated that the average slope of the lunar uplands is 52°. The tendency is accentuated by the lack of rainwash to segregate finer particles at the scree foot: waning slopes are doubtless barely developed. As the scree grows, the free face is progressively buried, whereas comminution of the fragments allows a gentle settling and flattening of the weathered material. In this way the craters will be infilled and their external margins littered with talus.

At this point, however, the requirements of the local base level are satisfied, and, if two "graviplanes" have been formed adjacently at different levels, an extremely slow transfer of material from the higher to the lower may be expected. This will go on in ever expanding regions until the whole surface of the spheroid becomes destitute of relief. In this sense an ultimate erosion-deposition surface may be expected, and interim erosion-deposition surfaces may be found. Though these interim forms may be flat over very large areas, there can be no hope of universal correlation (such as the eustatic hypothesis offers for the earth), until the absolutely final graviplane has been fashioned. It is readily apparent that, as relief fades, the effect of gravity must become weaker and weaker in promoting translocation. The senile stages of the cycle will be progressively decelerated and almost infinitely protracted in time.

But graviplanation does not operate alone. Resulting as it does from the absence of a lunar atmosphere, it is, in actuality, inseparable from the differentiation of the surface by meteorite bombardment. In one sense each impact represents an independent, localized rejuvenation, setting back the graviplanation cycle to begin its work all over again. In this light there are hundreds of thousands of separate cycles at different stages: each possesses its maximum relief right at the outset and works steadily toward its reduction. But in the larger view the upland areas, at least, may be regarded as the work of a single cycle which has never been interrupted by marine transgressions and is as old as the solidity of the moon's crust. Such a cycle progresses as the net result of competition between differentiation and graviplanation. In the early stages the smooth initial surface is progressively differentiated by impacts. This is the stage of youth, characterized, as in the humid temperate cycle of earth, by increasing relief. Continued bombardment leads to the consumption of the initial surface in the intercrater areas until the craters come to occupy the whole scene. This is the phase of maximum relief and may fittingly be termed the "onset of maturity." During youth, graviplanation is of negligible effect in comparison with differentiation, but, once maturity is attained, the power of the impacts to increase relief is diminished. They can best create mountainous

ringwalls out of compacted rock, and, as they strike the weakened material of former craters and weathered scree, they will eventually pulverize it and so flatten rather than raise it. This state of affairs will not become general until far into the future, but already there is some indication that it is not unknown. The small rimless crater pits which cast no exterior shadow may possibly be formed by small meteorites hitting dusty areas which are not sufficiently cohesive to be ridged up into ringwalls. If this is so, differentiation alone would lead to the formation of a pitted plain. Its late stages would offer less keen competition to graviplanation processes and would come to reinforce them. Weathering products would gradually infill the remaining pits. Thus, as with earth cycles, the lunar cycle tends "first to create relief, then to destroy it."

In formulating a denudation chronology, a twofold regional division must first be made. As already noted, the uplands are probably the direct heir of the original cooling surface of the young moon. They are now more or less continuously crater-scarred, and in stage they stand just on the threshold of maturity. The maria, however, represent a major rejuvenation: a second smooth initial surface was provided by the lava flows, which buried broad tracts of an earlier submature topography. Relatively few impacts have been registered since this episode, and the maria are still in a stage of early youth, with large expanses of initial surface still spreading between the craters.

It is possible to attempt the absolute dating of both these cycles. The mature surface of the uplands must display the sum total of achievement of the whole two or three thousand million years of the moon's solid history (cf. Jeffreys, 1924). A terrestrial humid cycle may perhaps take ten to twenty million years for its completion. This lunar cycle has already run roughly two hundred times as long and has still not advanced far into maturity. The youthful surfaces of the maria are also incredibly old in actual years. This can be determined from the fact that they share with the uplands in the form of the moon's fixed tidal bulge, indicating that the lavas were extruded before the tide became finally fixed. Jeffreys has calculated the date of this episode as sixty-five million years after the birth of the moon, when it was about 90,000 miles away from the earth. Hence the maria must be very early pre-Cambrian in age, and their slight progress into the stage of youth may have taken anything upward of a thousand million years. The extreme slowness of the lunar cycle cannot be overemphasized.

The relative dating of other lunar land forms clearly begins with their division into pre-mare or post-mare features. Into the latter class fall the rills, or cooling cracks, and also the younger craters which are either pitted into the lavas (e.g., Aristellus) or else have their rays splashed across them (e.g., Copernicus). Pre-mare features demonstrated by Baldwin's detailed observations include first the giant craters from which the lavas came. For example, the Caucasus Range, a detached arc outlining the Mare Imbrium, has its base buried in the lava and only its peaks protrude. Craters and valleys adjacent to the maria have also been invaded to varying degrees, and a larger number of craters have been tiled by the large-scale isostatic adjustments which lowered the maria to their present depths. All these features patently predated the lava flows.

On account of the random distribution of the craters, post-mare impacts should be equally dense on both maria and up-

lands. As Baldwin has shown, the maria are only sparsely pitted, and it seems likely that only 10 per cent of the present total can be of post-mare age. Thus 90 per cent were already formed in the first sixty-five million years of the satellite's evolution—well under a quarter of its whole life. One cannot escape the conclusion that the rate of impact has radically diminished with the passing eons. Moreover, there has been some tendency for the craters to lessen in size. Of the youngest group (Baldwin's Class 1), the vast majority are small, though a few of them range up to 85 miles in diameter. It has been suggested in explanation of this double trend that the moon early swept up most of the wandering cosmic matter in its orbit and that progressively less remains for it to acquire. If this is so, the decrease in impacts will continue systematically; the possibility of a second mare-forming episode is reduced; and the relative importance of graviplanation to differentiation will be considerably greater than outlined above on the assumption of a uniform rate of bombardment.

The craters can be arranged in order of age on several bases. The most obvious evidence lies in the intersection of one ringwall by another: that which remains entire is newer than that which is partially destroyed. Second, lamination or terracing of the inner wall suggests that there has not yet been time for the roughly horizontal irregularities of compressional uplift to be masked by local scree, and craters which possess them can be considered as relatively young. Third, ray systems are still clearly visible around the fresher craters but have been obliterated from the older ones. Fourth, the young craters are more deeply cup-shaped: their floors have not yet been infilled with weathered debris. Baldwin's suggestion of isostatic updoming in response to the removal of material from the center would similarly shallow the floor with increasing age. There is, however, no known example of a nearly filled crater, and it appears that some thousand millions of years must elapse before one can be expected.

CONCLUSION

The main conclusion drawn from this study is that, despite the enormous duration of time expended in the uninterrupted fashioning of the lunar surface, the morphological cycle is but little advanced. There is no suggestion that any single crater has as yet been obliterated by erosion, though many have been destroyed by later impacts or buried beneath the lavas. The extreme slowness in change is due to the restricted range of processes which can operate on a body devoid of both atmosphere and hydrosphere. Moreover, though differentiating agents have in the past been more successful in promoting change, there is clear evidence that these are waning in activity. The future morphological prospect of the satellite is of a scene where progressively less will happen and which, inconceivably slowly, will approach a condition of featureless stability.

REFERENCES CITED

BALDWIN, R. B. (1949) The face of the moon, Chicago, University of Chicago Press.

BONESTELL, C., and LEY, W. (1950) The conquest of space, London, Sidgewick & Jackson.

CAIRNES, D. D. (1912) Differential erosion and equiplanation in portions of Yukon and Alaska: Geol. Soc. America Bull. 23, pp. 333–348.

JEFFREYS, H. (1924) The earth, Cambridge, Cambridge University Press.

SHARPE, C. F. S. (1938) Landslides and related phenomena, New York, Columbia University Press.

WOOD, A. (1942) The development of hillside slopes: Geologists Assoc. London Proc., vol. 53, pp. 128–140.

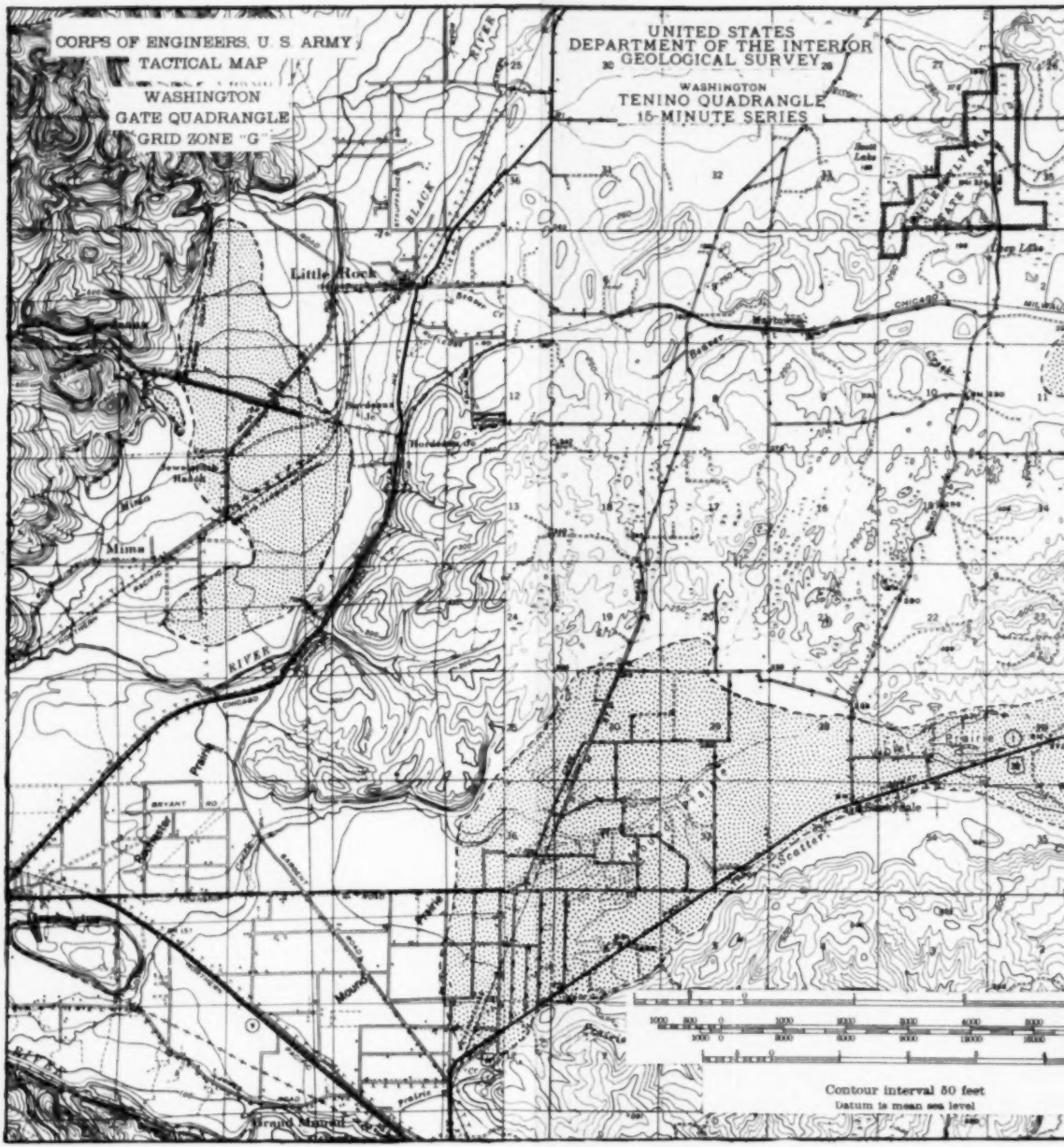
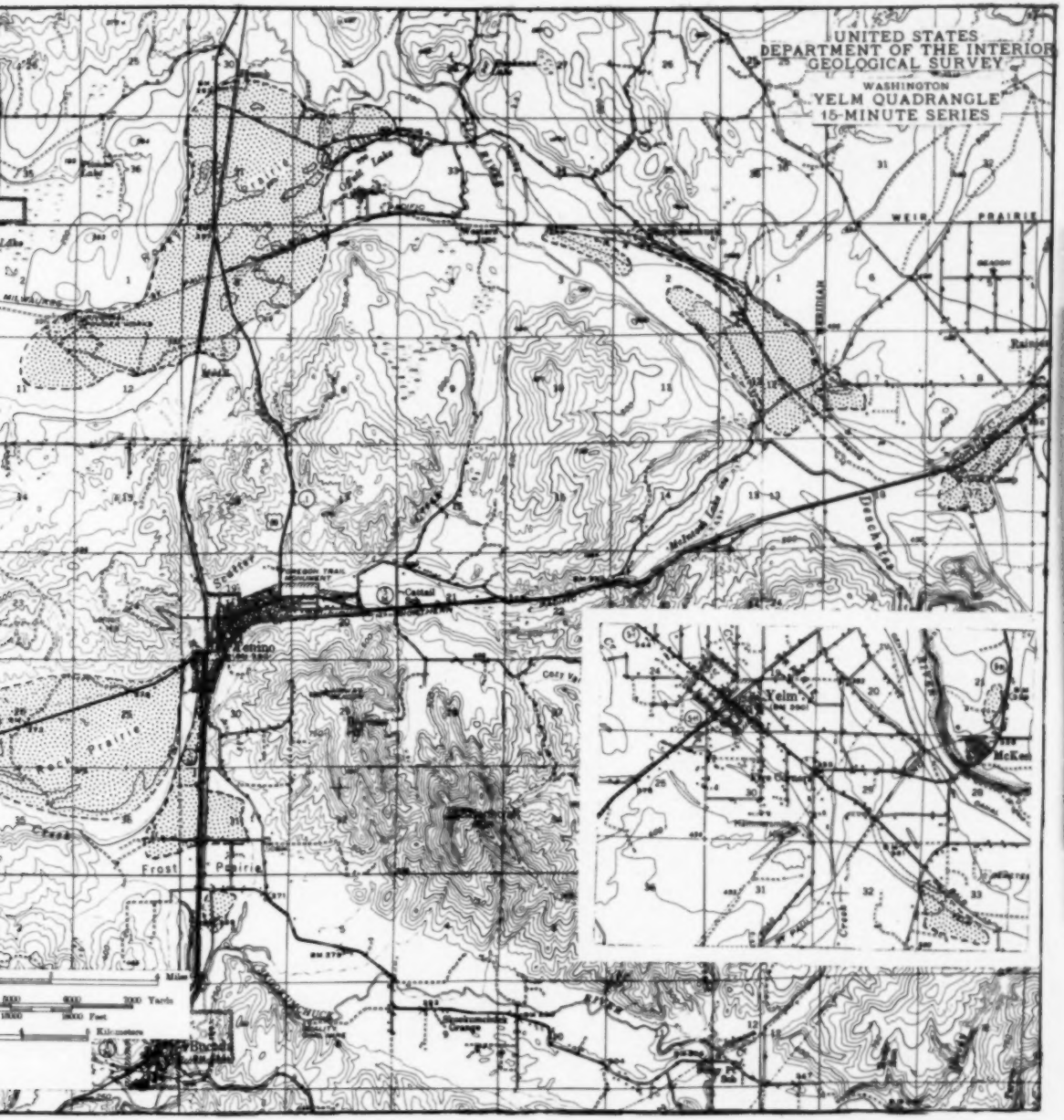


FIG. 1.—Map showing principal Mima mound areas (*stippled*), Thurston County



ounty, Washington. Inset, *lower right:* Yelm lies 5 miles northeast of Rainier

ORIGIN OF THE MIMA MOUNDS, THURSTON COUNTY REGION, WASHINGTON[1]

R. C. NEWCOMB
Portland, Oregon

ABSTRACT

There has been recent favorable consideration of the idea that the Mima mounds were made by gophers. The writer believes the evidence indicates that gophers function only in the reworking of the mound material, not in the primary construction. The plausibility of the earlier glacial or periglacial theory has been increased by recent knowledge of permafrost and of the deposits made by combined water and ice in cold climates. The gopher theory, as it has been applied to the Mima mounds, contains internal disharmonies and ignores significant field evidence supporting the earlier idea.

INTRODUCTION

In the southern Puget Sound region, south and southeast of Olympia, the outwash prairies of the Vashon glacial stage are marked by fields of strong natural mound formation (fig. 1). The mounds are among the most striking and best-known minor physiographic features of the Pacific Northwest. There have been great range and variety of hypotheses to explain the origin of these structures.

The hypothesis of gopher (*Thomomys telpoides*) construction of the Mima mounds was advanced by Dalquest and Scheffer (1942). Although an origin by gopher, mole, or ground-squirrel action has often been conjectured in discussions of the mounds, Dalquest and Scheffer's is the first publication of such a hypothesis of mound development in the United States. If gophers can make these mounds, they have a greater physiographic effect than heretofore supposed.

Bretz (1913) described the mounds in this region as belonging to two types, the Mima and the Ford. Only the Mima type is considered in this paper. This type is a uniform and symmetrical mound that apparently has but one general origin and habit, although there is a great variety of perfect and partial mounds. The principal features of the mounds are described briefly in this paper; the reader is referred to Bretz's excellent field observations for further details on the mounds and mounded areas.

The writer believes that the enigmatic origin of these mounds constitutes a continuous embarrassment and a challenge to geological science. Since 1942 the gopher hypothesis has been a popular thesis and is being projected indiscriminately elsewhere—to the Columbia Plateau by Larrison (1942), to the California mounded areas, and to Europe. Because it is believed that any such projection should be preceded by adequate establishment in the type area, the writer here maintains that many of the principal points of the gopher hypothesis are erroneous and argues for a return to the earlier concept of periglacial or glacial origin.

CHARACTERISTICS OF THE MIMA MOUNDS

MATERIAL

Mima mounds are composed entirely of black silt, sand, and pebbly gravel

[1] Manuscript received February 5, 1951.

mixed in all proportions (pl. 1, *A*). The material is friable, loose, and lacking in clay or plastic constituents. The pebbles in the slit have a maximum diameter of about 1½ inches.[2] The black carbon stain is attributed to the prairie-type vegetation that the silt characteristically supports (Nikiforoff, 1937). The black silt of the mounds is essentially the same in composition, texture, and structure as that which mantles most of the Vashon outwash prairies of the region, including those on which no mounds exist. Generally, the last and lowest channels of each prairie are partly devoid of this silt mantle and are lacking in good examples of these mounds.

TABLE 1

DIAMETER OF TYPICAL MOUNDS

Writer	Reference	Limits (Feet)	Average (Feet)
Bretz (1913)	Text, p. 82	6–60	.....
	Map, p. 96 (71 mounds)	21–55	42
	Photographs, pl. VIII	.....	40
Dalquest and Scheffer (1942)	Photograph, fig. 5 (1 mound)	60–65	.....
	Text, p. 69	6–40	20
Newcomb	Measured (400 mounds)	10–70	47
	Map, fig. 2 (17 mounds)	20–50	38

[2] Seven cobbles and boulders are reported to have been found in the mound soil (A. M. Ritchie, "Hemispheroidal Thawing and Erosion of the Mima Mounds," oral presentation, Northwest Science meetings, Spokane, Washington, December 29, 1950).

SIZE

All observers agree that in height the Mima mounds vary from low, barely recognizable forms to a maximum height of 7 or 8 feet. The large size of some Mima mounds is frequently cited as an objection to the gopher hypothesis. Because mound diameters given by Dalquest and Scheffer do not agree with Bretz's or the writer's observations, some data on average diameter of typical mounds are given in table 1.

SHAPE

The most nearly typical mound is the flatly hemispheroidal form commonly found near the center of mound groups. Its ground-plan outline is roughly circular but generally has some pronounced straight facets. Its surface profile passes laterally to the level of the gravel intermound surface with a gently upwardly concave curve. In general, the higher the mound, the more abruptly its slopes meet the intermound gravel floor. In profile some of the high mounds in central lower Rocky Prairie resemble giant downturned sauce bowls. Blanks in the pattern, dwarfs, and double- and triple-tied mounds are common (see map, fig. 2).

PLATE 1

A, The pebbly black silt of a mound overlying the gravel outwash (exposed in road bank on Rocky Prairie just west of Offut Lake).

B, A pronged depression in an unmounded portion of Frost Prairie. Prong reaching toward right background rises to prairie surface level but aligns with prong from the depression visible in the background. Flat prairie surface largely preserved in interdepression segments such as that to the right and to the left rear of the spade.

C, Linear exposures of cobbly submound gravel in polygonal pattern about a Mima mound on Frost Prairie. This type development adjoins and grades into the pronged depression type shown in *B*. The writer finds it difficult to entertain even a hypothetical gopher exposure of such intermound areas.

A

B

C

Features of the Mima Mound area, Washington

STRUCTURE

The typical mounds consist of a flat-bottomed spheroidal segment of black unstratified pebbly silt, rising above the outwash surface. Rarely, and where the mound lies on the finer phases of the submound material, the outwash beneath the mound is marked by a black-stained downward extension of the black prairie soil. The color and general soil characteristics of this downward extension are continuous with those of the structureless black silt of the mound proper, but this extension in many places shows pebble stratification similar to the adjacent submound material. The depth to which this black coloration extends into the underlying material is roughly proportional to the thickness of the black mound soil above, thus forming the lens, or biconvex cross-sectional shape, observed in some mounds by Bretz.

RELATIONS TO TOPOGRAPHY AND UNDERLYING MATERIALS

The outwash sands and gravels of the Vashon valley trains underlie the mounded prairies and mark the early southward outlet channels of the meltwater of the thick Puget Sound lobe of

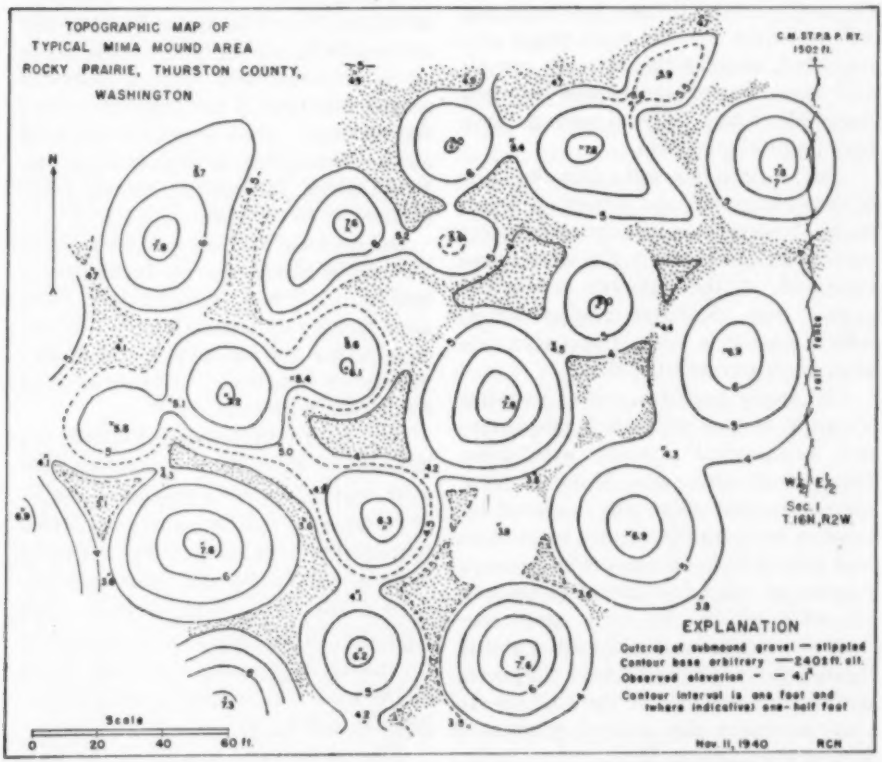


FIG. 2.—An incompletely mounded average area inhabited by gophers. It is suggested that any subsequent growth, if present, might in the future be measured by resurvey.

the Vashon glacier. The master-bedding dips downstream toward the Chehalis Valley (the trunk outlet) essentially parallel to the land surface, which slopes about 8–10 feet per mile (Bretz, 1913, p. 83).

At any one place the top beds of the outwash sand and gravel may be either strongly cross-bedded or accordant with the master-bedding. Thus the prairie soil commonly lies upon the beveled cross-beds of the subsoil sand and gravel. Each prairie surface commonly has several levels which step successively downward over sharp terrace descents toward the last outwash stream channel. On nearly every terrace the black silt soil, generally 1–3 feet thick where unmounded, overlies the outwash gravels and sands. Postmound erosion has been negligible. Many fields of mounds have been leveled by farmers.

The precipitation sinks into the loose outwash materials and drains off internally; however, on the lower terraces during the rainy season the intermound exposures of the outwash sands and gravels may discharge ground water, which flows off in integrated stream nets along the intermound swales.

Commonly, each group of mounds has a central area of complete hemispheroidal, symmetrical mounds, with wide, bare, intermound areas. Many of these mature mound areas are bordered by areas of less perfectly formed mounds as well as by peripheral zones of incipient or fragmental mounds adjacent to the unmounded prairie. In some areas immature mounds have a flattish segment located about halfway between the gravel surface and the tops of the mounds. It may represent the general premound level of the prairie surface.

The origin of the mounds can be studied much more advantageously in these areas of imperfect mounds around the edges of the mound groups than amid the billowing perfection of the more perfect mounds.

EXCEPTIONS TAKEN TO DALQUEST AND SCHEFFER'S PRESENTATION

ON FIELD OBSERVATIONS

1. *Size of mounds.*—Dalquest and Scheffer (1942, p. 69) asserted that "their basal diameters do not vary greatly from 20 feet." The writer found that 40–45 feet is a fair average and that the common range is from 10 to 70 feet.

2. *Spacing of mounds.*—On the subject of spacing, Bretz (1913, p. 83) observed as follows: ". . . The Mima type mounds are usually closely set. There is but rarely an intermound area with a diameter greater than that of the larger mounds of the vicinity." That statement is borne out by measurements from his map (pl. VIII), which show an aggregate average of some 53 feet between mounds.

Dalquest and Scheffer (p. 72) observed: "There is absolutely no regularity of spacing . . ."; but later (p. 80): "The areal spacing of Mima mounds is about equal to the spacing of individual gopher 'homes' or 'territories' in other parts of the Pacific Northwest. . . ."

Newcomb (1940) contended that the intermound spaces were a reticulate network, having a general polygonal, mainly hexagonal, pattern, and he inferred thereby that a spacing at least roughly uniform within any one group was the normal disposition of the mounds. This regularity of spacing, as well as some of the mound alignments, is actually shown in Dalquest and Scheffer's aerial photographs (their fig. 1).

This pattern and spacing in the Dalquest and Scheffer aerial photo and in the writer's vertical aerial photos of the

Mima-mound prairies are markedly similar to the pattern shown in Péwé's (1948) vertical aerial photos of the present ice-wedge mound fields near Fairbanks, Alaska.

3. *Relation of the mound soil to the submound gravel.*—Dalquest and Scheffer (p. 72) reported that the base of the "silt-gravel," where it is curved convexly downward in the biconvex mounds, truncates the stratification of the underlying gravel. Bretz (1913, pp. 95–96) stated that strata pass through the convex basal portion of the black silt. The writer also has observed[3] stratification in these convex basal portions and considered the lower part of the biconcave lens shape to be merely blackened portions of the underlying materials. Thus, if the downwardly convex segment beneath some mounds is to be considered part of the mound, it is erroneous to refer to the mound materials as "entirely unstratified," as do Dalquest and Scheffer (p. 73).

4. *Origin of the assorted character of the black prairie-soil materials.*—Dalquest and Scheffer (p. 84) considered the structureless soil of the mounds to be "evidence of gopher action." But the black silt on the mounded prairies, on the unmounded portions of the mounded prairies, and also on unmounded prairies of the region is as structureless and unsorted as that in the mounds.[4] Despite the structureless character common to both the mounded and the unmounded prairie soils and despite Dalquest and Scheffer's supposition that gopher action accounts for the assorted character of the mound soil materials, they asserted (p. 82) that certain unmounded prairies ". . . yield no traces of gophers."

5. *Exploratory burrows.*—This is the agency, according to Dalquest and Scheffer, by which the gopher transfers the material to make the mound. The excavations which they mentioned (p. 79) were limited to four 10-foot-long burrows. They considered that all the soil from two burrows and half the soil from two others had been taken into the mound to fill abandoned burrows. The evidence that this particular quantity of soil was "actually transported into the mound" was that it was not observed to be on the surface. Other possible dispositions for this material seem not to have been considered.

6. *Vegetation on the mounds.*—Dalquest and Scheffer (p. 77) observed: "It might be argued that gophers attracted to, and therefore feeding more intensely in the vicinity of their living quarters would reduce the vegetation rather than increase it. Actual observations, however, of mounds where gophers are actively working at the present time indicate that the vegetation is more luxuriant on the mounds than elsewhere in the vicinity (fig. 7)." However, this may well be the consequence of the originally deep mound soil and the thin soil in intermound areas.

The writer has observed that, where depths of mound and intermound soil are comparable, the vegetation on the mound is no heavier or "more luxuriant" than on the intermound or nonmounded areas. He is also convinced that gophers do devastate the vegetation of the mounds. In October, 1940, at the extreme northeast end of Rock Prairie north of U.S. Highway 99, the gophers were stoping the grass root-crowns and had converted to a fallow condition fully half of each of the many mounds; also they were ac-

[3] Well shown in the Northern Pacific Railway cut through Rocky Prairie, 1 mile west of Offut Lake.

[4] A good section of the black prairie soil of the unmounded areas is shown by Nikiforoff (1937, p. 208, fig. 6).

complishing a slight flattening action on these mounds by virtue of their raising of soil on the mound slopes. Nikiforoff (1941) observed a similar flattening effect by ground squirrels on mounds in the Great Valley of California.

7. *"Mound cobbles."*—Dalquest and Scheffer (p. 75) observed: "An irregular layer of mound cobbles often lies beneath the base of the mound lens. The mound cobble layer, as well as the intermound cobbles, is found only where cobbles of approximately the same size are present in the underlying gravel. Where cobbles are abundant in the latter, mound cobbles and intermound cobbles are abundant. Where cobbles are scarce or absent in the local stratified gravel, mound cobbles and intermound cobbles are correspondingly scarce or absent." That statement is largely paraphrased from Bretz (1913), p. 103) with the exception of the term "mound cobbles," which Dalquest and Scheffer used but did not define. Their observation and the coining of the term "mound cobble" would be unobjectionable if they did not later (p. 78, l. 21; p. 80, l. 6; and p. 83, l. 11) use it as a keystone evidence, or inference, of gopher origin. The true relation of the gravel and cobbles of the outwash gravel to the overlying black silt was well stated by Bretz (1913, p. 106): "Cobble strewing of the prairie surface is known at least locally to have antedated the formation of the mounds and requires no place in the conception [of mound origin]."

8. *Relations of Mima and Ford mounds.*—Dalquest and Scheffer (p. 73) observed: "A Ford mound may quickly be recognized by the fact that compact stratified gravel lies but a few inches below the surface of the mound, while in a Mima mound it lies several feet below." And also (p. 82), in taking exception to Bretz's hypothesis, they said: "Mima mounds, however, may occur on the flanks or tops of Ford mounds (fig. 2)." It seems that these observations must be faulty; for, if Mima mounds can lie on Ford mounds, then Ford mounds cannot be identified by their criterion.

9. *Relation of Mima mounds to other minor relief features.*—Dalquest and Scheffer observed that the Mima mounds occur upon the "grosser types of relief" (p. 82) and concluded therefrom that only gophers can effect this conformity to topography (p. 84, ll. 10–13). It is the writer's belief that other mound-making agencies (for example, ground-ice) can accommodate to gentle topographic variations, though the resulting mounds probably would not be so perfect as on plain surfaces. Such is the actual character of the Mima mounds found on steep or uneven slopes.

10. *Areal distribution of mounded prairies.*—Dalquest and Scheffer (pp. 81, 82) observed that the areal distribution of the prairies which carry Mima mounds and also gophers indicates accordance with their "gopher-origin" hypothesis. They listed as examples: Quillayute Prairie, which they considered analogous but for gophers, and Bush Prairie, analogous except for soil depth, in neither of which prairies did they find Mima mounds. Quillayute Prairie, on the northwest side of the Olympic mountains, is not comparable climatically now—and probably was not closely so in glacial times—with the mounded prairies. Its average annual rainfall is some 85 inches as compared to about 50 inches for the mounded prairies. It does not seem proper to observe such contrasting climatic situations as comparable sites for the delicate ecological processes postulated by Dalquest and Scheffer. Bretz (1913, p. 95) has stated that the Mima mounds are, with one exception,

confined to the outwash prairies of the eastern and lower lobe of the Vashon glaciation, only one faint occurrence being known for the western lobe.

Bush Prairie, 10 miles north of Tenino, also differs considerably as to soil and glacial history from the area in which Mima mounds occur. The Mima mounds are unique, and their absence from any distant place is irrelevant to the question unless it is first established that the place concerned has sustained the same geological, biological, and meteorological history since early Vashon times.

ON LOGIC

As Dalquest and Scheffer's hypothesis is largely developed by deduction and inference, it is necessary to examine some of their logic. The distinction between plausibility and proof is necessary to the evaluation of the gopher hypothesis. The reader is confronted with trains of thought such as are embodied in the following successions.

1. *"Exploratory burrows" as the method by which gophers accumulate the mound material.*—Dalquest and Scheffer, after developing the hypothesis that the mounds are the established centers of accretion (p. 78, ll. 23–24; p.79, ll. 4–6, 9–12), attempted to explain why mounds do not exist in areas having a deep soil. They averred (p. 80, ll. 24–27) that "exploratory burrows, i.e., shallow burrows radiating from a common center and shortly abandoned, seem to be formed only where gophers exist in areas rich in food plants surrounded by relatively barren areas." It is faulty logic to call the exploratory burrow the *cause* of the barren area (p. 79) ("accounts for the sunken contour of the intermound area") and on the succeeding page to declare the exploratory burrow to be the *result* of the barren area.

It seems more logical to accredit Dalquest and Scheffer's last observation (p. 80, ll. 24–27) that "exploratory burrows" are confined to "areas rich in food plants [i.e., the mound] surrounded by relatively barren areas [i.e., intermound area]" and to conclude therefrom that the "exploratory burrow," where present, is evidence only that gophers now living in the mounds have simply adapted their burrows to a situation they never created.

2. *Hypothetical permanent centers of soil accretion.*—Dalquest and Scheffer deduced (p. 80): "The voluntary restriction of an individual gopher to a small area, even where food is abundant in the surrounding territory, has been mentioned by many writers." When this statement is applied to the region of the Mima mounds, the reference "even when food is abundant in the surrounding territory" can conceivably mean only the deep soils (such as Bush Prairie) which Dalquest and Scheffer said are inhabited by gophers but are not mounded, for at no other gopher "centers" are there postulated peripheral conditions "where food is abundant." Then below, while developing an explanation for the lack of mounds or near-by areas of gopher-infested deep soils, they conjecture: "Where gophers are living in regions of deep soil, mounds are not formed, for burrowing is as easy in one spot as in another and nesting centers have no tendency to become fixed." Thus, in one sentence, gophers are inferred to be areally restricted by habit even in areas of abundant food (deep soils) and a motivating reason for the mounds is inferred, then it is said that mounds are not formed in aforesaid deep soils because there are no areal restrictions whatsoever to cause a locus of accretion ("nesting center").

It is fundamental for the reader of Dalquest and Scheffer's hypothesis to realize that no field observations are known which record that the gopher concerned has ever systematically or accidentally continually accumulated earth about any center of accretion. The writer has observed that these gophers, the region over, in settings like the mounded prairies or in other places, are entirely fortuitous in the direction of aggregate ultimate movement and discard of their excess excavations.

3. *Mound materials.*—In Dalquest and Scheffer's summary of evidence for gopher origin of the Mima mounds they stated (p. 81): "The Mima mound is constructed entirely of soil materials small enough to be moved by gophers." But when one notes that such soil also composes some of the nonmounded prairie soils (Dalquest and Scheffer, 1942, p. 69, ll. 10, 11) which these authors say were not gophered, this argument fails to support their conclusion. They state also: "Materials too large to be moved by gophers appear beneath the mound or in the intermound region." This seems irrelevant, as Bretz (1913, pp. 102–106) described such occurrences:

> The intermound cobbles were probably not deposited or aggregated by the agency which formed the mounds. They have not gravitated to the intermound areas from an original equitable distribution subsequent to formation of the mounds. Cobbles of the intermound type are not known to occur in the gravel and silt of the mounds, but are found in the stratified gravel immediately below them. Where the cobbles are large, the gravel below contains large stones, and where the cobbles are lacking or represented only by large pebbles, the subjacent gravel is deficient in fragments of cobble stone size.

4. *Age of the mounds.*—Dalquest and Scheffer (p. 76) considered the mounds to be definitely younger than the kettles which in places occur in the outwash prairies. But the case for a prekettle age is equally good, for, within definite kettle depressions, there are poorly formed mounds which could reasonably have been altered by the settling incident to the formation of the kettles.

The melting-out of a deeply buried ice block probably would not have destroyed all the mounds in such places. There are many kettles devoid of recognizable mounds, although they occur in the midst of well-mounded prairie levels. The kettles in the prairie surface just south of Old Muck Post Office on Fort Lewis Reservation are examples of this type.

ON OMISSIONS

The following points are considered pertinent to the problem of mound origin but are not mentioned by Dalquest and Scheffer.

1. *Degree of completion of the mounds.*—The perfection of the true spherical shape and symmetry has been observed by the writer to be greater toward the centers of strongly mounded areas and to be less perfect outward to the peripheral zones, where partial or immature mounds may predominate.

2. *Aberrant types of mounds which obviously do not fit the gopher hypothesis.* (*a*) *Low, thin mounds.*—The low, thin mounds that are in places less than 1 foot high and are surrounded by peripheral swales devoid of the silt soil occur at the western end of Grand Mound Prairie and on the sloping eastern margin of upper Mima Prairie. The conception of these low, flat mounds (where in places the soil is scarcely deep enough to cover a large gopher) as gopher accumulations and "homes" seems incongruous.

b) *Ringed mounds.*—Ringed mounds, such as those found on the prairie south of Old Muck Post Office (Bretz, 1913,

p. 90), lie widely spaced and are surrounded individually by a band of submound gravel exposed in the lower intermound zone, which, in turn, is surrounded by a peripheral ridge raised to the height attained by the mound. No agent or process advanced by Dalquest and Scheffer could conceivably be postulated for these peripheral ridges.

c) Pronged depressions.—Pronged depressions occur in some unmounded areas adjoining mound areas. On Frost Prairie north of Bucoda, in an otherwise even, unmounded part of the prairie, there are linear branched hollows, abruptly sloped, angular in ground plan, and up to 4 feet deep,which expose gravel without a soil cover. They commonly have three branches whose bottoms rise outwardly within some 10–20 feet to the prairie level. The branches line up with those from neighboring hollows to form a polygonal network of linear depressions incompletely surrounding flattish-topped segments of the general prairie level (pl. 1, *B*).

In other cases the depressions are larger and are fully interconnected, with the resulting enclosed hillock possessing a more or less spheroidal shape. All stages can readily be discerned, from the first sharp depressions in an otherwise unmounded prairie to the complete typical mound area (pl. 1, *C*). These depressions are genetically related to the principal mound-building process which, when carried further, has produced a typical mounded area. These depressions are not compatible with Dalquest and Scheffer's hypothesis. They were not mentioned by them.

3. *Mechanics.* (*a*) *For removal of soil from wide bare intermound zones.*—Some intermound swales expose the clean stratified submound gravel for a width of 20–40 feet. There is little or no vestige of silt soil on these strips and no evidence of its having been eroded away or having penetrated into the gravel below. The agency which formed the mounds must have been responsible for some of these wide intermound areas. Dalquest and Scheffer failed to explain how their hypothetical "exploratory burrow" agency could effect this complete soil removal (in some places it would have had to accomplish a virtual sweeping action). It is difficult to imagine gophers having done this.

b) For sharp separation of mound from intermound.—Likewise, it is hard to visualize how any such "exploratory burrow," or other gopher system, could produce the sharp, even margin separating the mature mound from its intermound strip.

ORIGINS PREVIOUSLY POSTULATED

Bretz (1913, pp. 105–106), after reviewing all earlier opinions, suggested a tentative hypothesis consisting of a modification of the "concentration of washed drift in holes in a melting ice sheet." This hypothesis, he indicated, could hardly explain more than a part of the mound occurrences, and its details must await the detection of similar processes in existing piedmont glaciers or ice sheets. He considered the origin as not fully explicable on the basis of data then available. In summarizing his "limitations of a successful hypothesis," Bretz (p. 105) said:

> Agencies which might have operated under the limitations above enumerated are practically limited to ice and water, either of which may have been standing, or moving, or both. . . . If ice was present it obviously was in fragmental masses from the adjacent glacier or had formed on the surface of standing water beyond the ice.

That such a process can, in some cases, form Mima-like mounds is now

known. Similar mounds formed on the flood plain of the Colorado River below DeBeque, Colorado, during the winter of 1945–1946. There, during a period of subzero temperatures, ice formed upstream from the DeBeque Canyon dam. Subsequent flow into the reservoir repeatedly flooded over this ice and froze, thus building up a considerable thickness of dirty ice. After the thaw and spring breakup, very dirty ice from 6 to 10 feet thick was left stranded on the margins and on the upstream gravel bars. These ice remnants cracked into separate pieces in a roughly systematic pattern, and flood currents washed between them. As the river stage subsided and the ice blocks melted, the dirt from each ice block accumulated in a pile which sloughed down to a low mound of roughly circular plan. These mounds are largely silt with some sand and gravel. Some of the more symmetrical mounds reach a height of 4 feet and a width of 12 feet (Wayne M. Felts, personal communication, 1946).

A somewhat similar process, forming moundlike "kames," has been observed by Nichols (1936) in Maine, where stream outwash was deposited over the accumulated snow of one winter.

It seems possible that such a process may have operated repeatedly and on a large scale toward the close of the melting of the early eastern lobe of the Vashon ice, as postulated by Bretz.

The growth of two marked mounds as reported by Koons (1948) lacked evidence of either growth or gopher construction. They can hardly be taken as evidence for the construction of mature Mima mounds in five years, as stated recently by Price (1949). Likewise, the ground swells and sags reported by Bailey are not believed to be the evidence they are alleged to be by Price.

A partially developed hypothesis ascribing the origin of the mounds to the deposition and erosion work of outwash streams was advanced in a personal communication in 1947 by R. L. Lupher. He cited the general uniformity of mound heights within any one mound group, the common alignment of mounds along terrace escarpments, and the distribution of mound prairies only along outwash prairies that stem from glacial moraines as evidence favoring an origin connected with meltwaters.

A vague water-and-wind origin has been proposed recently for these mounds by Krinitzsky (1949), but his reasoning springs largely from study of aerial photos of the Mississippi Valley mounds and lacks a factual basis for the Mima mound occurrence.

Newcomb (1940) postulated an origin somewhat similar to Bretz's tentative hypothesis but used as the activating force local areas of late Vashon ground-ice of the fissure-polygon type, such as Leffingwell and Nichols have described, and which is now in places forming mounds and tortoise-shell topography in northern Canada and Alaska. Under this hypothesis it was postulated that during the early stages of the wasting of the Vashon ice a periglacial climate permitted the development of ground-ice of the fissure-polygon type in the surficial pebble-silt mantle.

Ice wedges, polygonal in pattern, might have thickened laterally and thrust the silt into center spaces, where it remained and sloughed down into mounds upon the melting of the ice wedges. The principal objections listed by the writer were the great width of the intermound spaces in the low, widely set mounds and the lack of corroborative evidence of the former existence of such a periglacial climate. Both these objections implied that the hypothesis might become more

tenable as research extended our knowledge of periglacial agencies.

The impetus of wartime construction in areas of permanent frost brought out several important contributions to our knowledge of permafrost, among them Taber's (1943) description of the Alaskan polygonal ice-wedge occurrences. Taber rather satisfactorily established that the growth of ice wedges is due to simple additive crystallization rather than to the freezing of liquid water which had run into shrinkage cracks in the ice wedge. This correction simplifies the mechanical explanation of ice-wedge phenomena as a possible constructional agency for the Mima mounds.

The writer visualized the ice-wedge thrust as producing an over-all bulging of the mound area, not the throwing-up of a marginal ridge, as implied by Dalquest and Scheffer (p. 83, l. 21). It is noted that in a recent publication on present mound-forming ice wedges at Fairbanks, Alaska, Péwé (1948, fig. 1) shows pictures of ice-wedge-formed pronged depressions, which show that an over-all interwedge swelling must have taken place in the incipient mound areas.

The concept of the frost polygon as a possible Mima mound-building agency must assume that the wedges widened and thickened above outwash gravel to a maximum height possibly greater in places than the present height of the largest Mima mounds. That such magnitude is possible was suggested by Leffingwell, who noted Maydell and Toll's descriptions of vertical inclusions of earth in heavy bodies of ice at Siberian localities and suggested that these might represent an advanced stage of ice-wedge growth.

Dalquest and Scheffer raised several "objections" to the frost-polygon hypothesis. Among them were: the failure of the ice-wedge hypothesis to account for "mound cobbles," etc.; the belief that ice wedges could hardly have formed mounds at the bottoms of kettles, tops of Ford mounds, and lips of terraces; the observation that in some cases not all silt is removed from some intermound areas; the presence of isolated mounds without any surrounding polygonal ridge; the difficulty in visualizing how ice wedges could have formed imperfect mounds; and the failure of the pebbles to show the shattering supposed to be a consequence of a periglacial experience.

The writer thought that the periglacial hypothesis adequately explained all the mound features which are accountable by the normal vagaries of ice wedges—such as imperfect mounds, partially constructed mounds, and poorly built mounds on uneven slopes. Contrary to Dalquest and Scheffer's statements, it is believed that the topographic distribution of the Mima mounds conforms quite well to that of the recorded habit of ice-wedge developments. The pebble shattering is similar to that in gravels of similar lithology in the regions of present permafrost. There are but minor amounts of schistose, sedimentary, or other foliated pebbles in these gravels, and the massive granitics, basalts, quartzites, and similar types are no less shattered than in many regions of present periglacial climate.

There may be some evidences of a former periglacial climate in that area. For example, on the gravel terraces, just east of the Mima–Gate road at a point about 4 miles south of Mima station and nearly a mile east of Gate, there are, in the unmounded soil, linear and polygonal concentrations of pebbles which the writer takes to be stone-stripe effects of periglacial origin. Though the forest

soils could scarcely be expected to preserve the periglacial structures and there are few areas in the region devoid of forests, careful search may in the future reveal other evidences of a former periglacial climate.

In view of the inconsistencies in the gopher hypothesis as presented by Dalquest and Scheffer and the above factors favoring a glacial or periglacial origin, the writer believes the true origin of these widely known mounds can best be sought by returning to the requirements listed by Bretz and applying our increasing knowledge of glacial and periglacial agencies.

REFERENCES CITED

Bretz, J H (1913) Glaciation of the Puget Sound region: Washington Geol. Survey Bull. 8, 244 pp.

Dalquest, W. W., and Scheffer, V. B. (1942) The origin of the Mima mounds of western Washington: Jour. Geology, vol. 50, pp. 68–84.

Koons, F. C. (1948) The sand mounds of Louisiana and Texas: Sci. Monthly, vol. 66, pp. 297–300.

Krinitzsky, E. L. (1949) Origin of pimple mounds: Am. Jour. Sci., vol. 247, pp. 706–714.

Larrison, R. J. (1942) Pocket gophers and ecological succession in Wenas region, Washington: The Murrelet, vol. 23, pp. 34–41.

Newcomb, R. C. (1940) Hypothesis for the periglacial "fissure polygon": Origin of the Tenino mounds, Thurston County, Washington (abstr.): Geol. Soc. Oregon Country, Geol. News Letter, vol. 6, p. 182.

Nichols, R. L. (1936) New mechanism for the formation of kettleholes and eskers (abstr.): Geol. Soc. America Proc., pp. 403–404.

Nikiforoff, C. C. (1937) The inversion of the great soil zones in western Washington: Geog. Rev., vol. 27, pp. 200–213.

——— (1941) Hardpan and microrelief in certain soil complexes of California: U.S. Dept. Agr. Tech. Bull. 745, p. 29.

Péwé, T. L. (1948) Origin of the Mima mounds: Sci. Monthly, vol. 66, pp. 293–296.

Price, W. A. (1949) Pocket gophers as architects of Mima mounds of the western United States: Texas Jour. Sci., vol. 1, pp. 1–17.

Taber, Stephen (1943) Perennially frozen ground in Alaska: its origin and history: Geol. Soc. America Bull. 54, pp. 1433–1548.

SUBMARINE "NATURAL LEVEES"[1]

EDWIN C. BUFFINGTON
U.S. Navy Electronics Laboratory, San Diego, California

ABSTRACT

Natural levees fringe subaerial streams of low gradient which periodically experience overbank floods onto wide floodplains. Submarine features, resembling these natural levees, have been found in several places off the West Coast of the United States. A study of occurrences at ten localities at depths of from 600 to 3,600 feet shows (1) that transverse profiles may be symmetrical or asymmetrical, with one "levee" higher in the latter case; (2) that the channel between the "levees" may be U- or V-shaped; (3) that the tops of "levees" may be 24–408 feet above the adjoining channel bottom, and (4) that these tops may be 12–204 feet above the immediately adjacent sea floor.

It is believed that these features may be the products of turbidity currents or submarine mudflows.

INTRODUCTION

In the last three years the accelerated program of bathymetric studies carried on by the United States Navy Electronics Laboratory has resulted in the discovery of several types of small submarine topographic features. Among the more interesting of these are "natural levees" bordering small submarine channels.

Natural levees border the channels of some subaerial rivers in the late-mature and old-age stages of development and are also prominent on large deltas (Russell, 1942, pp. 75–77). They are mentioned and briefly described in most basic texts in geology and geomorphology, and complete agreement appears to exist on the mode and conditions of formation (Russell, 1936, p. 72). The subaerial stream builds its natural levees in times of flood when it is heavily laden with sediment. As the river becomes swollen and exceeds the confines of its channel, it spreads out over the floodplain. The decrease in velocity as the water leaves the channel causes deposition of the coarser elements of its sedimentary load. In some places the levees are built up to such an extent that they are the only land visible in a completely inundated floodplain.

Submarine natural levees are as large as, or larger than, comparable subaerial features, but they are relatively small compared to other submarine topographic features which have been studied and are usually not detected in bathymetric surveys based on discrete soundings, especially in deep water. Recording echo sounders, giving a continuous trace of the bottom profile, provide greater detail on the configuration of the sea floor. Furthermore, some recording echo sounders are adapted to record detail, customarily obtainable only in shoaler water, at considerable depth. The profiles of submarine natural levees figured in this paper were recorded by instruments of this type.

DESCRIPTION

Table 1 lists occurrences of submarine natural levees at ten localities. Depth below sea-level, levee height above channel and surrounding area, channel shape, and profile symmetry are indicated for each locality.

Echo-sounding traverses across submarine natural levees reveal profiles which resemble profiles across subaerial

[1] Manuscript received September 10, 1951.

levees. The central figure is a channel, commonly V-shaped, which is bordered on each side by an embankment which rises perceptibly above the level of the surrounding area. In some profiles (see pl. 1, *B*) the channel bottom is above the level of the surrounding area. This is characteristic also of some subaerial streams with natural levees (Lobeck, 1939, p. 224). The surrounding area is generally flat, although a few of the natural levees are found on gentle slopes. Off San Clemente, California, levees are believed to border a channel which runs down a slope of at least 5° (see table 1).

Subaerial natural levees, which border large streams, commonly have broad, gently sloping tops, several hundred feet wide, although they may be narrower on smaller streams. Figure 1 shows profiles

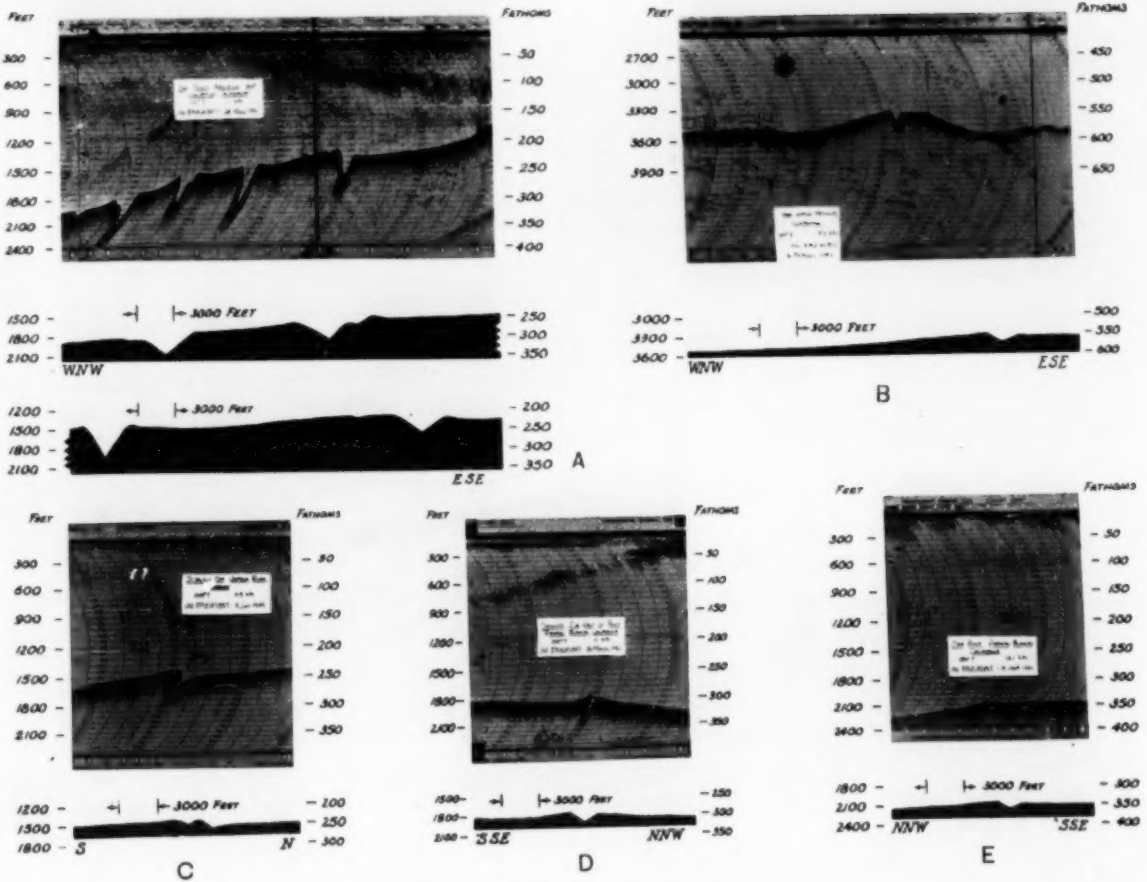
TABLE 1

OCCURRENCES OF SUBMARINE NATURAL LEVEES

LOCATION	DEPTH (BELOW SEA-LEVEL)		LEVEE HEIGHT*				SYMMETRY†	SHAPE OF CHANNEL	REMARKS
			Above Channel		Above Surrounding Area				
	Feet	Fathoms	Feet	Fathoms	Feet	Fathoms			
San Diego Trough, Calif. (pl. 1, *B*)	3,390	565	90–120	15–20	204	34	A	V	Elevated channel
Off Point Arguello, Calif. (pl. 1, *A*)	1,320–1,818	220–303	204–432	34–72	12–24	2–4	A, S	V	Three channels leveed
Due west off Point Piedras Blancas, Calif. (pl. 1, *D*, *E*)	1,830	305	126–156	21–26	84	14	A	V	Two crossings of the same channel
	2,100	350	84–108	14–18	18–60	3–10	A	V	
Off the Umpqua River, Ore. (pl. 1, *C*)	1,440	240	132	22	60	10	A	V	One levee only
Continental slope off Huntington and Seal beaches, Calif.	600	100	24–48	4–8	12	2	A	V	Crossing obliques general contour of slope
Continental slope off San Pedro, Calif.	684–816	114–136	60–108	10–18	12	2	S	V	Two channels leveed
San Diego Trough, Calif. (at foot of Coronado Ridge)	2,976	496	144–168	24–28	24–48	4–8	A	U	
Off Rocky Point, Calif.	3,600	600	180–408	30–68	60–120	10–20	A	V	
San Clemente, Calif.	1,800	300	150	25	72	12	?	U	Only one bank detailed; flat channel bottom (transversely) on 5° slope
San Diego Trough, Calif.	3,360	560	60	10	30–162	5–27	A	V	Channel elevated; continuation of channel shown in pl. 1, *B*

* The figures in these columns indicate the range of levee heights above the channel or the surrounding area if there are several channels at the locality, or of the two bordering levees in the case of a single channel.

† "A" = asymmetrical; "S" = symmetrical.



Profiles across Pacific coast submarine channels

across the natural levees along the banks of the lower Mississippi River just above New Orleans. Artificial levees have been built on top of the natural levees, but these are differentiated in the profile. One interesting, and perhaps significant, characteristic of some submarine levees is an asymmetry in transverse profile.

Plate 1, *B*, is an echo-sounding profile across a levee-bordered submarine channel which runs down the center of a broad, flat submarine depression known as the San Diego Trough. The depth at the profile crossing is 3,390 feet. This channel is V-shaped in cross section and in this respect differs from the profile

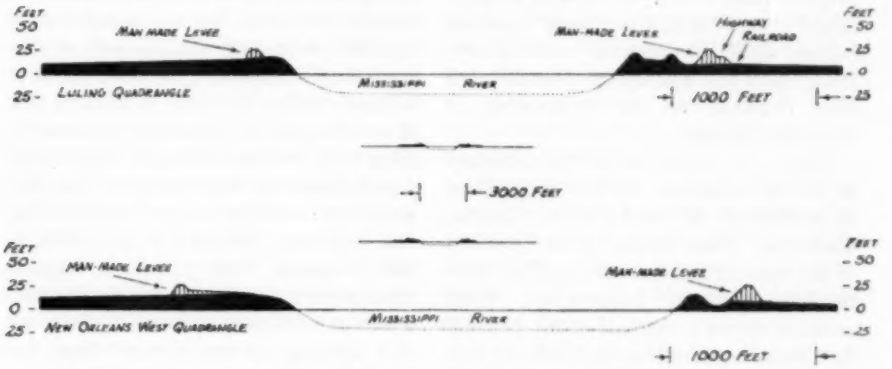


FIG. 1.—Profiles across the lower Mississippi River just north of New Orleans. Artificial levees built on natural levees are indicated. The small insert profiles are reductions to the approximate scale of the profiles shown in plate 1. Vertical exaggeration is 6.34×. Profiles taken from the U.S. Geological Survey topographic sheets of the Luling and New Orleans West quadrangles.

Most natural levees along subaerial channels are built up equally on each side of the stream where the channel is straight, although "the most widespread and thickest natural levee deposits occur on the outside of bends" (Fisk, 1944, p. 18). Many pairs of submarine levees have one levee higher or broader than the other, or, in one place, a levee only on one side (see table 1 and pl. 1, *C*).

shown in figure 1. However, it is known that the lower Mississippi River has filled its channel with alluvium and that the bedrock profile approaches a V-shape. Plate 1, *B*, shows that one levee is shoaler (higher) by at least 30 feet than the other. The former has a sharp crest while the latter is flat.

Plate 1, *A*, shows four channels on the continental slope off Point Arguello,

PLATE 1

A, Echo-sounding profile across four submarine channels off Point Arguello, California. Vertical exaggeration of blocked profile, 5×.

B, Echo-sounding profile across a submarine channel in the San Diego Trough, California. Vertical exaggeration of blocked profile, 5×.

C, Asymmetrical submarine channel off the Umpqua River, Oregon. Vertical exaggeration of blocked profile, 5×.

D, *E*, Two crossings of a submarine channel off Point Piedras Blancas, California. Vertical exaggeration of blocked profiles, 5×.

California. The course of the ship was somewhat oblique to the contour of the continental slope (as shown by the general shoaling of the profile). Embankments border at least three of the channels, and one of these three definitely has the asymmetrical profile just discussed. These four channels are the only ones listed in table 1 that can be seen on published charts (U.S. Coast and Geodetic Survey 5202, or Shepard and Emery, 1941, chart II). The charts also show the four channels to be tributaries of Arguello Canyon.

Plate 1, *D* and *E*, show two crossings of leveed channels on the continental slope directly off Point Piedras Blancas, California. These appear to be crossings of the same channel on the basis of independent position information. Each crossing shows a channel about 108–120 feet deep, bordered on each side by natural levees. Each profile shows one levee to be higher than the other, although the more seaward crossing shows the differential to be less.

Plate 1, *C*, shows a crossing of the continental slope, just off the Umpqua River, Oregon. The channel shown has one embankment which is further complicated by an additional small channel (?) running down the center of it. The northern side of the main channel has no abrupt boundary but rises gradually and smoothly until it attains the general level of the local sea floor. Because this record (pl. 1, *C*), like practically all the others, is a single crossing, the possibility remains—and cannot be ignored—that the lack of a levee on one side may be due to the confluence of a tributary at this particular spot.

DISCUSSION

The information currently available precludes anything other than the most general statements regarding origin of these levees. Some speculations and ideas are presented in the hope that they may provide a working hypothesis for subsequent investigations.

The presence of a prolonged channel on a slope or a flat generally indicates a continual, periodic, or episodic current. Of the several types of currents known to exist in the ocean, few are thought to be capable of eroding the bottom at any great depth. Studies have been made of bottom-eroding currents in harbors and at shoal depths in the ocean; but what is known of bottom currents below shelf depths indicates that they have velocities which are capable only of transporting fine sediment (Shepard *et al.*, 1939, p. 489; Shepard, 1948, p. 66). It appears reasonable to assume that the channels which have been described are the result of a flowing current of some type, because several are known to extend over considerable distances.

The presence of the natural levees bordering a submarine channel suggests that this bottom current or flow has at least some behavior similar to that of a subaerial stream which forms natural levees. The most important of the characteristics causing the behavior would be a heavy sediment load. The type of bottom current which would meet this requirement best is the turbidity flow.

Although the presence and efficacy of turbidity currents to erode the sea floor are subject to considerable question, some authors invoke them to explain the origin of submarine canyons. It has been established, however, that they can carry a large sediment load in a fresh-water environment (Grover and Howard, 1938; Bell, 1942, pp. 542–545; Gould, 1951). If such currents are present in the ocean and if they flow down constricted channels or develop channels, it is reasonable

to suppose that their behavior with regard to deposition is comparable to that of a sediment-laden subaerial stream. The effect of the bottom of the channel and its banks on the turbidity current would be essentially the same as the effect of the bottom and banks on a river. The basic difference would lie in the effect of the other confining boundary. The air mass above a river exerts negligible effects, but the water mass above a turbidity current must have a marked effect on the turbidity current. For example, turbulent diffusion and drag effects are likely (Menard and Ludwick, 1951), although as yet not measured.

The basic laws of sediment transport should apply to a turbidity current, and it should deposit some of its load at any point where the velocity decreases. Only two of many possible causes of decreased velocity are considered.

1. A turbidity flow, moving down a slope within the confines of a channel, reaches the bottom or an area with a gradient much less than that of the channeled slope. Here the confining channel may or may not continue. In either case the momentum of the flow will carry much of it forward, but the net effect is a loss of velocity which results in deposition. If the confining channel does not continue, the flow may build one with banks near its periphery because the central body of the flow would continue forward at a greater velocity than the margins. Net deposition would be greater at the margins because of the greater velocity decrease, and a channelway with levees would result. If there is a preexisting channel, it may be overflooded, if the volume of the flow exceeds the volume which the channel could contain, with the consequent formation of levees.

2. Shepard (1948, pp. 195–198) and others give evidence for the existence of slumps and slides under the ocean. Such a slump or submarine slide occurring on the wall of a sea valley or gully might partially constrict the channel. If the the velocity of a downflowing turbidity current is not great enough to remove the slumped material speedily, the flow may be diverted upward, spread out, and flow beyond the confines of the channel. The check in velocity at the point of overflow would cause deposition. Of course, this is not the only locus of sedimentation because of the velocity check, but it is one which might explain a local occurrence of natural levees on a slope.

The development of the asymmetrical profile, indicating excessive sedimentation on one bank, poses additional problems. One possible explanation is presented, although little field evidence bears on the concept.

Daly (1942, p. 143, fig. 73) figures a chart of a channel on the Rhone delta in Lake Geneva, Switzerland. This channel is known to be the product of low-velocity turbidity currents, although the mode of formation is moot. Kuenen (1950, p. 510, fig. 227) also figures this chart and in his discussion suggests that differential deposition, rather than erosion, was responsible. The chart shows that embankments have developed along the sides of the channel. In some places only one side has a levee, and in the others, where levees are present on both sides, one is higher than the other. The channel is somewhat sinuous, and the higher levees, or single levees, are mainly on the outside of a curve.

One submarine channel in table 1 with natural levees has a sinuous character (R. S. Dietz, personal communication). This channel originates where La Jolla Canyon debouches into the San Diego Trough, and its winding course has been traced across the floor of the Trough to

the approximate vicinity of Thirtymile Bank (see Shepard and Emery, 1941, chart I). Most of the profiles crossing the channel show natural levees. Near the base of Thirtymile Bank the crossing figured in this paper was made (pl. 1, *B*). Surveying was not accurate enough to determine whether there is any correlation between the asymmetry of the natural-levee profiles and the bends in the channel, but if this is the case, as in Lake Geneva, a possible mechanism to account for the phenomena is suggested.

A turbidity flow coming down a channel tends to oppose changes in direction of flow because of its momentum. On reaching a bend in the channel, the flow tends to behave something like a bobsled going around a banked curve. It rises on the outside bank, in an attempt to maintain its direction. Some of the flow might go over the edge of the bank, with the consequent formation of a levee. Because the main mass of the flow is thrown to the outside of the curve, the levee developed there is larger than on the inner side.

Sharp (1942, pp. 222–227) has described small levees formed by the action of mudflows moving down alluvial slopes of the St. Elias Range, Yukon Territory. Unsorted bouldery alluvium comprises the levees, and they are formed by the shouldering-aside of the material by the stream of mud. He compares the action to that of a snowplow and further describes some of the mudflow levees as having higher embankments on the outsides of curves.

Mudflows have not been observed in the ocean, but it is reasonable to presume that a submarine slump or slide might be transformed into one which would move downslope. This mechanism has been discussed by Menard and Ludwick (1951). The order of magnitude of the levees described in this paper almost surely precludes action such as Sharp describes, but it may be possible that mudflows, acting under much the same basic principles as turbidity flows, could be responsible for levees.

Turbidity currents grade into mudflows by the addition of sediment, and the distinction between a very dense turbidity current and a watery mudflow is usually made arbitrarily. R. S. Dietz (unpublished manuscript entitled "Geomorphic Evolution of the Continental Terrace") suggests that the two be distinguished on the basis of density versus flow-velocity relationships. For a given slope, the velocity of a mud-water slurry increases with density only up to a certain point, beyond which there must be a decrease in velocity because of increased viscosity. This point, where the velocity decreases in spite of an increase in density, may be usefully considered as the transition between a turbidity current and a mudflow. The movement of mudflows is generally considered to be slow and nonturbulent. The arguments cited for turbidity currents would, in large part, apply to mudflows.

The presence of asymmetrical levees, however, especially if they exist on the outsides of curves, argues for turbidity currents rather than for mudflows. A turbidity current, with a density which may be low relative to a mudflow, would have a much stronger tendency to swing out at curves because of the lesser effect of the gravitational component of force with respect to momentum.

H. R. Gould (unpublished manuscript) reports the presence of levees bordering a channel down the front of the delta formed where the Colorado River flows into Lake Mead. The levees rise as high as 4 feet above the surrounding area, and their development along

the main channel has, in some places, been extended across the mouths of tributaries, partially blocking them off. Gould attributes the formation of these features to deposition from turbidity currents.

Perhaps both mudflows and turbidity currents are responsible. A thick mudflow, by dilution and mixing, might become a turbidity current, and the two acting jointly or successively would form levees.

SUMMARY AND CONCLUSIONS

Levees which border submarine channels are similar in form to natural levees which border some subaerial rivers. Of the ten submarine channel localities described, eight have channels with asymmetrical transverse profiles, showing that a levee on one side has been built up preferentially.

Submarine levees are tentatively explained as the result of deposition from turbidity currents or possibly mudflows. If one levee is larger than the other, it may be caused by a flow overriding the outer edge of a curve in the submarine channel.

ACKNOWLEDGMENTS.—The echo-sounding records on which this paper is based were taken aboard the "U.S.S. EPCE(R) 857," a research vessel of the U.S. Navy Electronics Laboratory. The writer thanks R. P. Sharp, of the California Institute of Technology, and H. W. Menard, R. S. Dietz, and R. D. Russell, of the U.S. Navy Electronics Laboratory, for constructive criticism of the manuscript.

REFERENCES CITED

BELL, H. S. (1942) Density currents as agents for transporting sediments: Jour. Geology, vol. 50, pp. 512–547.

DALY, R. A. (1942) The floor of the ocean, Chapel Hill, University of North Carolina Press.

FISK, H. N. (1944) Geological investigation of the alluvial valley of the lower Mississippi River: Mississippi River Comm., Corps of Engineers, U.S. Army.

GOULD, H. R. (1951) Some quantitative aspects of Lake Mead turbidity currents; in: Turbidity currents and the transportation of coarse sediments to deep water: a symposium: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 2.

GROVER, N. C., and HOWARD, C. S. (1938) The passage of turbid water through Lake Mead: Am. Soc. Civil Engineers Trans., vol. 103, pp. 720–790.

KUENEN, PH. H. (1950) Marine geology, New York, John Wiley & Sons, Inc.

LOBECK, A. K. (1939) Geomorphology, New York, McGraw-Hill Book Co., Inc.

MENARD, H. W., and LUDWICK, J. C. (1951) Applications of hydraulics to the study of marine turbidity currents; in: Turbidity currents and the transportation of coarse sediments to deep water: a symposium: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 2.

RUSSELL, R. J. (1936) Physiography of the lower Mississippi River delta: Louisiana Geol. Survey Geol. Bull. 8, pp. 3–199.

——— (1942) Flotant: Geog. Rev., vol. 32, pp. 74–98.

SHARP, R. P. (1942) Mudflow levees: Jour. Geomorphology, vol. 5, pp. 222–227.

SHEPARD, F. P. (1948) Submarine geology, New York, Harper & Bros.

——— and EMERY, K. O. (1941) Submarine topography off the California coast: canyons and tectonic interpretation: Geol. Soc. America Spec. Paper 31.

———; REVELLE, R.; and DIETZ, R. S. (1939) Ocean bottom currents off the California coast: Science, vol. 89, pp. 488–489.

A HIGH-LEVEL BOULDER DEPOSIT EAST OF THE LARAMIE RANGE, WYOMING[1]

J HARLEN BRETZ AND LELAND HORBERG
University of Chicago

ABSTRACT

A narrow belt of granitic boulders weathered from a pebble and cobble conglomerate and occupying the highest mesa and butte summits of the region extends for about 18 miles out on the Tertiary plain east of the Laramie Range in Platte County, Wyoming. The conglomerate is judged to be a record of a vigorous late Tertiary river which managed to move 20-foot boulders 18 miles on a gradient of not more than 75 feet to the mile. Field evidence supports this interpretation and does not permit favorable consideration of any other hypothesis.

INTRODUCTION

There are numerous boulder deposits in the Rocky Mountains whose modes of transportation are unsolved problems. Probably different agencies have operated in different cases, and perhaps two or more have co-operated in some cases. The concept of fluvial origin of the particular deposit herein considered is difficult to accept because of (1) an abundance of very large boulders, (2) an apparently inadequate gradient of the original floor on which they were moved, and (3) the considerable distance the deposit extends from the mountains. Nevertheless, the evidence seems to allow no other interpretation.

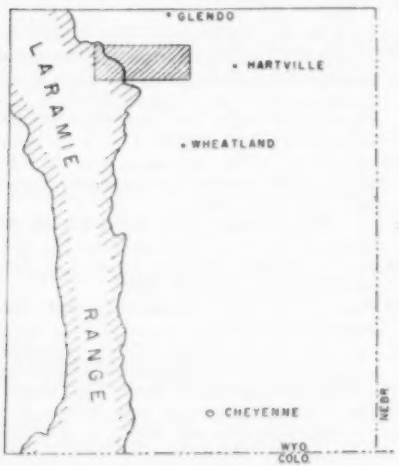


FIG. 1.—Index map showing area studied

DESCRIPTION

A prominent linear group of mesas, buttes, ridges, and conical hills in Platte County, Wyoming, all capped by a bouldery deposit, extends eastward from the foot of the Laramie Range out onto an erosional plain cut on White River (Oligocene) and Arikaree (Miocene) sediments (figs. 1, 2). Their summits rise to the level of the highest land surfaces in the county, except for portions of the Laramie Range and the Hartville Dome, and are clearly silhouetted on the northern or southern horizon for distances of 20 miles or more.

The fourteen summits involved in the group have an eastward-descending gradient of about 75 feet to the mile along the slightly sinuous course, approximately the slope of all lower adjacent divides paralleling it on the plain (Esterbrook, Cottonwood Falls, Coleman Butte, and Herman Ranch quadrangle maps). Although now constituting the crest of the interfluve between two

[1] Manuscript received October 15, 1951.

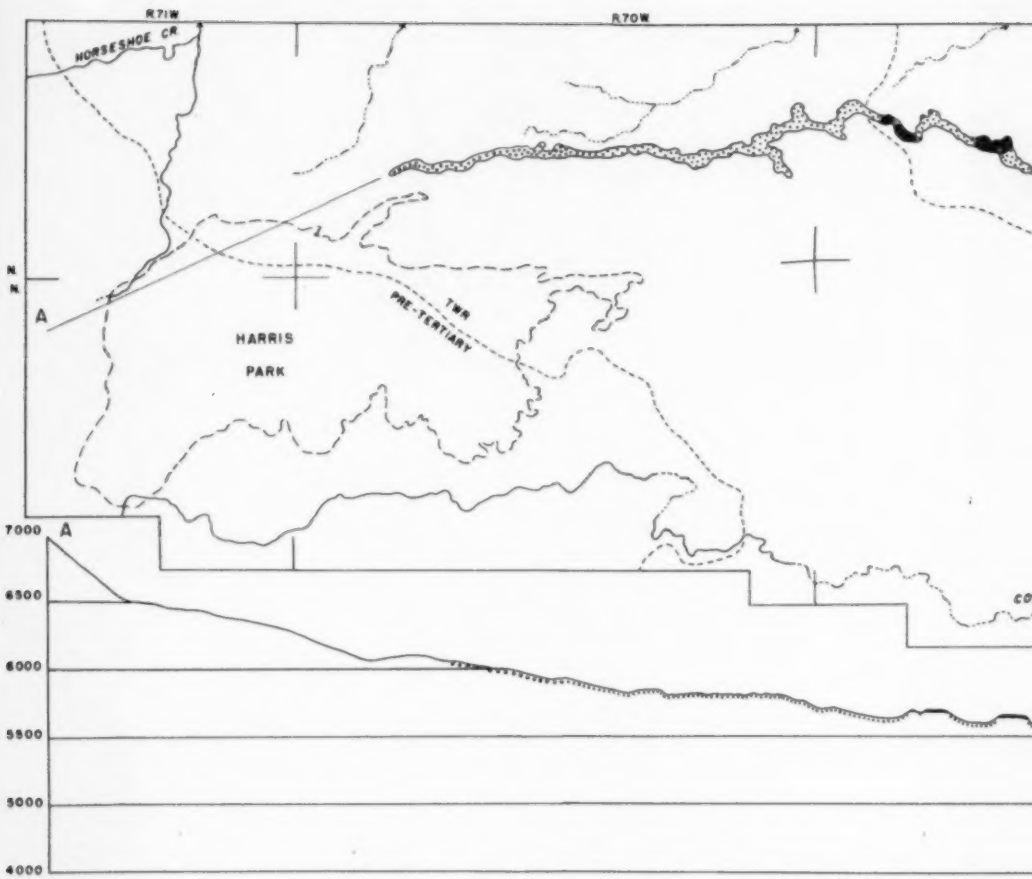
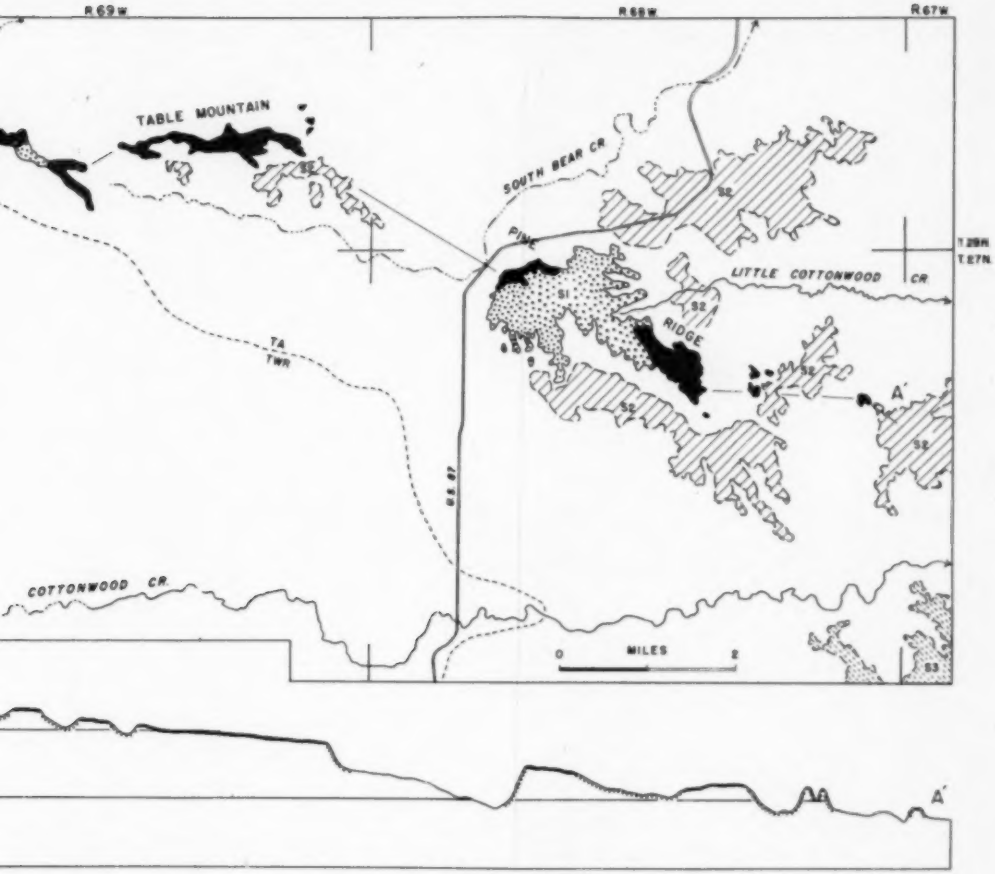


FIG. 2.—Boulder gravel *in situ* (*solid*), scattered boulders (*dotted*), and erosion surfaces east of the Laramie Range. The symbol surfaces. Dashed lines show generalized boundaries of pre-Tertiary rocks, White River formation (*Twr*), and Arikaree sandst



ymbol *S1* shows a local intermediate surface between the boulder gravel surface and *S2; S2* and *S3* show extensive lower andstone (*Ta*), based on the Geologic Map of Wyoming (Campbell *et al.*, 1925).

mountain-born streams, Cottonwood and Horseshoe creeks, its bouldery cap marks a former lowland transportation route. The relief of the plain has become inverted since the boulders were deposited.

Two places are known where this deposit is indurated and has a cliffed outcrop. Elsewhere it is only the cobble and boulder fraction released by weathering from the conglomerate which is obvious, either in place on the grassed summits or in present-day travel down the steep hill slopes. Judged from the best exposures, most of the material is a stratified pebble conglomerate with interstitial sand and a few sand lenses and strata. The maximum thicknesses observed are 30 and 50 feet, and thicknesses up to 100 feet have been reported (Love *et al.*, 1949). Imbrication indicates eastward flow of the ancient stream.

Boulders occur throughout the entire thickness and along the entire length of the deposit. In a cliff on the easternmost butte of the series (E. ½ Sec. 12, T. 27 N., R. 68 W., on the Hartville and Herman Ranch topographic maps but not shown on the geologic map by Smith and Darton [1903] in the Hartville folio) there is one bed with a dense boulder population, numerous boulders being in contact or near contact. Both below and above this bed are several feet of pebble conglomerate without boulders showing in the section.

Another feature of boulder distribution, seen on the summits and the brinks of flat-topped hills, is a habit of occurring in groups or clusters, clearly an original feature of the deposit (pl. 1, *B*). Some flattish or elongated boulders that are apparently still *in situ* stand edgewise or even endwise in the deposit. Unfortunately, none stood where the substratum could be examined.

Pebbles and cobbles of the deposit record a considerable variety of parent-rock, but among the thousands of boulders seen all were of granite, gneissic granite, and gneiss.

The boulders may average 5 or 6 feet in diameter. Many are 10–15 feet, and some are 20 feet in maximum diameters (pl. 1, *A*). There is no progressive decrease in size or abundance of boulders with increasing distance from the range. Indeed, the western slope of Pine Ridge, one of the larger flat-topped hills of the series close to U.S. Highway 87 and 10 miles in an airline from the mountains (fig. 2), shows as great an abundance of the boulders and as many examples of 20-foot specimens as any place seen.

The source of the boulders seems obvious when tracing of the linear deposit toward the mountains brings the investigator up short against the good-sized hills of granite that partially enclose Harris Park, on the Esterbrook quadrangle. Here the boulder-strewn belt, reduced from a mesa-top deposit to somewhat lower ridges but strewn with great boulders, ends abruptly against steep hills of granitic rock, deeply weathered along joints and disintegrating into boulder-clad slopes at even lower levels than that of the ridges noted.

Boulders on the flat summits of the ridges and mesas are much weathered. Exfoliation is not so common as is breaking along planes of weakness. Many original boulders are now only piles of separate fragments. Crumbling is common. Some have weathered cavities that hold a pool of rain water. Many are reduced to a cone shape above the surrounding soil, and some are weathered down to a flat surface at the soil level. Boulders migrating down the hill slopes are less weathered, having been more recently released from the cap gravel. All boulders, how-

ever, have so deteriorated from weathering both before and after release that no original surfaces are preserved.

So far as shown, the boulder deposit rests with sharp contact on pebbleless, sandy Tertiary beds. Although one place showed 4 or 5 feet of relief in 50 feet along this contact, no evidence for marked channeling was seen.

In the easternmost cliffed exposures there is evidence for scour during deposition of the pebble gravel, channel-like depressions holding a pocket of cobbles and in one case a boulder above the cobbles. Where a lens of sand and granule gravel underlies a boulder, it is judged to be only interstitial fines introduced later into unfilled cavities among the larger fragments.

Virtually no fragments, from pebbles to boulders, show much wear on the edges of fracture-block outlines of the original pieces. Some of the angular and subangular forms, lying on the surface, are due to fracture since deposition. But even in the cliffed exposures of indurated material, subangularity is a marked feature. Percussion marks are exceedingly rare, and no markings characteristic of glacial action were found.

In gravelly phases of the Arikaree sandstone exposed elsewhere in the region the writers found no stones larger than about 15 inches in maximum diameter and no bed of gravel more than a few feet thick and a few tens of feet long in the section. Some highway cuts show intercalated gravel and coarse sand lenses, making a cumulative thickness of 20 feet or more. Most of the Arikaree here is composed of sandstone and siltstone with impure limestone layers, and the gravelly portions are exceptional.

A significant feature of the indurated portion of the deposit is jointing, the dominant set running at right angles to the edge of the steep slope in subjacent Arikaree sandstone (pl. 1, *C*). The joints actually cut cobbles up to 7 inches in diameter, recording an even firmer induration than at present. There can be no reasonable doubt that this induration and jointing were produced under an adequate cover, that it is not a consequence of case-hardening and of settlement and fracturing on the present slope.

There are no detailed geological maps of the area, but the regional maps (Campbell *et al.*, 1925; Stose, 1932) and maps of adjoining areas (Smith and Darton, 1903; Spencer, 1916, pl. 4; Denson and Botinelly, 1949; Love, Denson, and Botinelly, 1949) indicate that the boulder gravel rests on the Oligocene White River deposits near the mountain front and extends eastward across beds of the Miocene Arikaree sandstone. A very generalized boundary, based on the Geological Map of Wyoming (Campbell *et al.*, 1925), is shown in figure 2. These relations, evidencing important erosion of the Tertiary beds prior to gravel deposition, suggest a Pliocene age for the boulder gravel.

PLATE 1

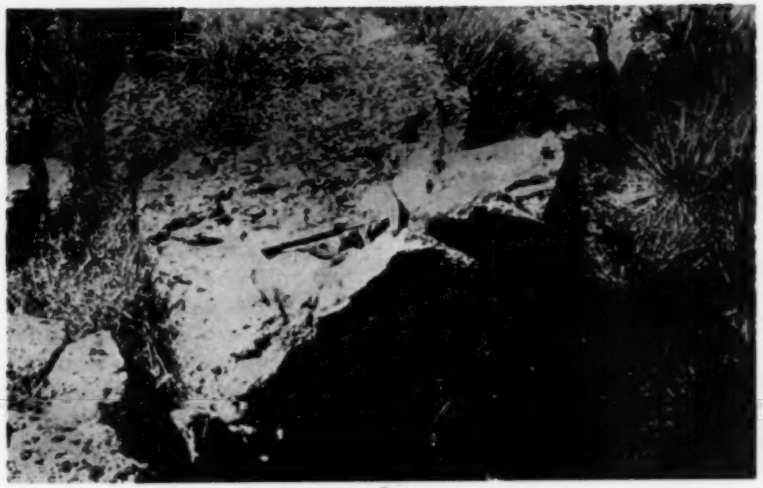
A, Large boulder of granite gneiss, over 15 feet in maximum diameter, on Pine Ridge (NE. ¼, Sec. 4, T. 27 N., R. 68 W.). Shows differential weathering and splitting due to weathering.

B, Cluster of granite gneiss boulders and boulder-clad slope on south side of Table Mountain (SW. ¼, Sec. 26, T. 28 N., R. 69 W.). Pine Ridge with White Arikaree cliff in distance. Ridge crests in the intervening area are close to the level of the *S2* erosion surface.

C, Boulder-gravel conglomerate containing 2-foot boulders and showing well-developed joints, east end of Pine Ridge (center, S. ½, Sec. 12, T. 27 N., R. 68 W.).

A

B



C

Boulder gravel conglomerate

INTERPRETATIONS

The attention of the writers was called to this boulder deposit by C. J. Hares, who had examined briefly the easternmost portion. Before the field study was undertaken, conversations were had with D. L. Blackstone and other geologists who had seen the astonishing display of boulders on the western slope of Pine Ridge, in plain view from U.S. Highway 87. Some of these informants indicated various tentative opinions regarding age and origin, and Love, Denson, and Botinelly (1949) have considered it a fluvial deposit of Quaternary age. During the field study, the writers changed their working interpretation at least four times, finally concluding that the deposit is of late Tertiary age, probably Pliocene, and that the field evidence records only fluvial transportation of the material.

That the boulder gravel is an integral part of the Upper Tertiary sequence, exceptional as it is when compared with the rest of the deposits, is argued from the jointing displayed on the easternmost butte. This jointing could hardly have been produced in a superficial deposit such as a Pleistocene channel fill on an Arikaree surface. The picture of Tertiary burial of the Laramie Range, drawn by numerous students of the region to explain the surviving high Tertiaries on the west side of the range, the "Gangplank" on the east side, and the Laramie River canyon across the range allows the Miocene Arikaree and later Tertiary deposits on the Great Plains slope of the range to have had an original thickness adequate to account for this jointing. There are also pebble shapes in the deposit which suggested strongly to the junior author that pressure deformation had occurred locally under load.

The objective of the field study—an understanding of how the huge boulders were transported—was only partially attained, viz., a determination of the agency. Its *modus operandi* remains speculative.

Of all alternative explanations, the one most readily disposed of is that of a granitic thrust sheet, now reduced by erosion to one linear remnant on the major divide of the overridden country. No facts support this view; all but the existence of the boulders deny it.

Boulders do migrate well beyond the outcrop source in piedmont waste slopes. Trowbridge (1911) has studied a case where boulders up to 30 feet in maximum diameter traveled 6 miles down a slope of 3°–6° and thought that undercutting on the downslope side unbalanced and overturned such boulders. Those he investigated rest on such fine material, which exhibits some stratification and is but little worn, as in the case in question. The objection to this hypothesis for the Platte County deposit is the low gradient, less than 1°, on which it lies. Whether or not it is a part of the late Tertiary sequence, it assuredly never had a depositional gradient approaching 400 feet to the mile. If anything, a present gradient somewhat steeper than the original is indicated by possible Pleistocene rejuvenation evidenced by canyon-cutting in the Laramie Range.

Trowbridge found that the boulders on the Sierra bajada he studied lay prevailingly in long trains descending the slope and radiating from the heads of fans. To apply this concept to the Wyoming deposit, one must ask that subsequent erosion destroy all trace of the original fan except this one boulder train—an exceedingly improbable thing.

Mudflows carry mixed sizes and actually float huge boulders on low gradients for short distances beyond mountain-valley mouths (Conway, 1893; Pack,

1923; Blackwelder, 1928), but their mechanism cannot provide for the stratification described. And what the Platte County boulders are embedded in is not mud. It is cobble and pebble conglomerate with a sand matrix. However, the boulders in the section constitute a definite bed, and it is conceivable that a mudflow might have spread over already deposited stratified gravel and had its mud matrix removed by immediately following stream flow, which filled interstices with sand and gravel and finally buried the boulder bed in pebble gravel.

It might be conceived that the boulder bed in the section described is part of a "stone river," the bouldery debris of an elongated solifluction flow left after later stream action had removed the finer material. This explanation faces the grave objection that a marked and very brief climatic refrigeration is required to bring the solifluction flow 18 miles out from the mountains, there to lie on and be promptly buried by stream gravels recording a different climatic regimen. The idea does provide, however, for the undisturbed subjacent gravel: it was frozen solid at the time of the boulder transportation.

The hypothesis of glacial origin must inevitably be tried on this deposit. It has more merit than any of those already considered, for glacial ice could transport the boulders on the gradient they did use and associated meltwater could produce stratification of the debris in favored places. Also, the grouping or clustering of boulders might well be the consequence of glacial transportation and deposition. But a glacier debouching from the mountains on a plain would probably develop a piedmont splay foot. It could not flow for nearly 20 miles out onto the plain as a valley-type glacier unless there was a sufficiently deep valley there to control its form. If there was, the debris should occupy two ridges instead of one, each recording a lateral moraine, and there should be a terminal accumulation in the record. The failure to find any striae or glacial faceting on the thousands of cobbles and boulders examined on the surface and in the indurated deposit or anything resembling till balls in the stratified gravel is well-nigh fatal to the glacial hypothesis. Furthermore, physiographic relations and induration indicate that the deposit is not of Pleistocene age, and no late Tertiary glaciation is more than suspected in the Rocky Mountains.

Nevertheless, glacial transport might be visualized for the initiation of the trip out on the plains, river-borne bergs then carrying the boulders farther along, to drop them on the stratified pebble gravel. But a river large enough to float a berg ballasted with a 100-ton boulder might well be large enough, on that gradient, to roll the boulder bodily along the bottom of the channel. River surface ice is no substitute for berg ice, and the stratified pebble gravel beneath boulders shows no distortion that grounding of large ice masses would produce.

A possible way to use ice as a co-operating agency is to consider that it was anchor ice, the ice formed on the bottom of streams, which, if detached, may float off with traction-load materials attached. If frozen to a bottom boulder, such ice would reduce the specific gravity of the mass and would also increase the surface on which the stream operated. Boulders thus shifted from season to season of anchor-ice formation in a sufficiently large stream conceivably could travel the full 18 miles on the existing gradient by a series of short journeys, and some might come to rest in the unstable positions previously noted. This concept, however, asks for travel in midwinter, which in a

cold climate is the season of low water.

The original width of the deposit can be only approximated. None of the remaining flat summits is ½ mile wide, although nearer the mountains, where dissection has left only ridges, the scattered boulders record a belt nearly 1 mile wide. An original width of 1 mile would conform to the needs of some of the suggested modes of origin but would favor none of them.

A curious feature which debars a determination of both the original width and the original length is the disappearance of boulders after migration down the butte and mesa slopes. Thanks to the boulder-conglomerate cap, these slopes retreat parallel to themselves, and there should logically be many surviving large boulders on the lower and younger surfaces left by this retreat. None was seen more than ½ mile out from any scarp base. In the largest gap among the boulder-capped hills, 3 miles long, no large boulders were seen on either gully slopes or the low ridge crests. Yet the deposit must have once been continuous across this gap. Except for patchy loess and very local fan and gully-bottom deposits, no burial of such boulders has been possible. They seem to have disintegrated, either completely or to such small sizes that their character has been destroyed.

Because nothing has been found in the deposit which would prove co-operation of any other agency with running water, the writers turn finally to the quantitatively rather vague concept of flash-stream floods. In lieu of mountain-stream gradients, transporting velocity must be found in volume. The boulders were already outlined by deep weathering along joints. Perhaps undercutting secured them. Perhaps repeated earthquake shaking of the outcrops loosened them and gravity brought them down to the valley bottom. But here they must have stayed unless that agent of transportation—the record is only of running water—had boulder-carrying competence or was aided by unrecorded co-operating agents adequate to distribute them all along the transportation route.

If the larger ones were stranded near the mountains and only smaller ones were carried for the full 18 miles, one might drop his querying and rest on the concept of flash floods. But 20-foot boulders traveled at least 15 miles from the nearest source. Equally puzzling to a proponent of mighty flash floods must be the survival of pebble gravel already deposited in the channel and receiving the great boulders with little evidence of the expectable scour.

Storm-made flash floods shrink into insignificance when compared with floods from bursting reservoir dams. Failure of the St. Francis dam in California released a flood that carried pieces of concrete, weighing many thousands of tons, for half a mile down the valley (Worcester, 1939, p. 165). Failure of the landslide dam on the Gros Ventre River, Wyoming, produced a flood (Alden, 1928) which transported boulders up to 15 and 20 feet in diameter. Failure of glacial dams in Alaska, the Himalayas, and elsewhere, with tremendous resulting floods, are on record. The senior author (1935, p. 185, figs. 272–274; p. 203, fig. 308) has described one in Greenland, where boulders up to 10 feet in diameter were carried out to the very edge of a sea-level gravel delta.

Exploring this idea of a bursting reservoir dam, one may visualize blocking of the mountain valley which led to the Platte County boulder deposit, either by a glacier descending a minor tributary valley (as in the Greenland case) or by a landslide, mudflow, or earth flow. Either

cause might at intervals produce recurrent floods. The boulders might already be in the valley bottom or might be brought there in the landslide.

No field evidence can be still surviving for support of this suggestion, and it must face the objection that pebble gravel already in the valley deposit still underlies the boulders brought by the hypothetical flood. To that objection may be returned the answer that no one knows how much pebble gravel actually was removed or how fully loaded with finer debris the supposed flood was when it arrived at the easternmost butte, where the best section of the deposit now exists.

If the stream in flood was excessively muddy, another factor enters the problem: the increase in buoyant effect of such water. Woodford (1924, p. 235) states that calculations with Sudry's formula indicate that "a medium composed of 25% clay and 75% water will transport blocks nine times as large as those carried by pure water."

The clustering or grouping of boulders must have had a specific cause in the action of the transporting agent. We can visualize boulder bars or boulder jams (Krumbein, 1942, pp. 1364–1369) in a stream, or we may call for stranding of floating ice masses or deposition from a glacier. The phenomenon does not admit of precise interpretation.

The conditions which gave the river its ability to move these boulders appear to have been abnormal and were followed by conditions under which no boulders were in transit. During these intervals, it was an aggrading river, depositing sand and gravel in its channel. Only enormously increased volume during exceptional episodes could give such a river ability to transport boulders. Thus, in spite of the recognized difficulties in acceptance of the hypothesis of flash floods from bursting reservoir dams, the writers at present have no alternative.

PHYSIOGRAPHIC RELATIONS

The flat tops of the larger surviving hills look like graded surfaces made during deposition of the gravel. The jointing, however, if correctly interpreted, requires that these flat summits be the products of later erosion. This view is supported by the existence and physiographic relations of another high-level gravel deposit of considerably different character. It caps the mesa about midway between Guernsey and Wheatland, Platte County, near the cornering of townships 25 and 26 north and ranges 66 and 67 west (on the Hartville topographic map, but not shown on the geological map in Hartville Folio No. 91, U.S. Geological Survey). Its altitudes range between 5,000 and 5,100 feet A.T., approximately the same altitudes as the Pine Ridge butte tops carrying the boulder gravel, some 10 or 12 miles to the northwest. This deposit contains no boulders. About 50 per cent of its well-worn, percussion-marked cobbles and pebbles are of massive quartzite, unlike the schistose quartzite represented in the boulder gravel. Other lithological differences in material of the two deposits, particularly the low percentage of granite in the boulderless gravel, clearly indicate two rivers from different drainage areas. The striking differences in shapes and sizes of stones imply that the two rivers operated under different regimens and probably were not contemporaneous.

This well-worn, boulderless river gravel, lying 5 miles or so north of the Laramie River's present course and 600–700 feet higher, is taken to be a record of that river early in the dissection of the Tertiary cover of the mountain range, before

the trans-range canyon was cut. Its high content of quartzite may indicate that the Snowy Range of the Medicine Bow Mountains was contributing debris. At any rate, this gravel had a much longer journey from hard-rock sources to its resting place than did the presumably older, boulder gravel.

Supporting evidence for a younger age of the old Laramie River gravel seems to exist in the relations of another broad upland at 5,000–5,150 feet A.T., about 12 miles east of Wheatland in T. 24 N. and R. 65 and 66 W. and separating Laramie River on the northwest from Goshen Hole on the southeast. This upland has no gravel cap and no very flat summit area. Instead, it possesses several cliffed buttes of sandstone rising above the general upland level, one hill reaching an altitude of 5,450 feet A.T. The upland is an erosional plain on the Arikaree, only slightly higher than the gravel-capped mesa 10 or 12 miles to the northwest with the Laramie Valley midway between.

Further support for the concept that these two uplands record an early erosion cycle on the weak Arikaree rocks lies in the existence of a faulted monoclinal flexure in that formation a few miles east of Wheatland and apparently striking northward between these upland tracts. From the little the writers know of the region's structure, this feature appears to debar any picture of the two uplands as structurally the same.

This digression from the theme of the boulder gravel deposit has been to show that the flat graded mesa tops may be satisfactorily interpreted as parts of the early oldland surface above described. The superjacent cover under which the induration and jointing developed was removed during this cycle. Only a 200-foot hill of Arikaree rock (Secs. 18, 19, 20, T. 24 N., R. 65 W.) remains within the limits of the Hartville and Esterbrook quadrangles above the trace of that early planation on the weak Tertiary sediments. It is this erosional level which appears to transect the Tertiary fill in those pre-Tertiary embayments in the range, Harris and Ullman parks (fig. 2).

Pedimentation apparently was favored by the climate during this cycle, for the flat erosional surfaces on Tertiary sediments blend into limited cut plains on pre-Cambrian rock, ending in steep, bouldery mountain slopes. As far as the writers have seen, this feature exists in favorable places from Ullman Park on the north to Sybille Creek basin on the south. Its bearing on the present problem is to add weight to the writers' belief that the boulder conglomerate of Platte County is much older than early Pleistocene.

The boulder belt began to attain its present topographic eminence when a new cycle of erosion was inaugurated, and, although it has been losing area in all subsequent time, it has been gaining in vertical prominence. For a long time it stood barely 150–200 feet above a second extensive leveling-off of Arikaree rocks in its environs (*S2*, fig. 2). This later cycle nearly destroyed the record of the earlier one. Its flats, now some 400 feet above major valley floors, are conspicuous features of the regional landscape. Although locally much dissected by later erosion, many crests of ridges between minor drainageways consistently fall into the same profile, descending from the mountains toward Platte and Laramie rivers and Sybille, Chugwater, Cottonwood, and Horseshoe creeks.

ACKNOWLEDGMENTS.—The writers are indebted to the Department of Geology, University of Chicago, for funds covering field expenses and to J. D. Love for criticism of the manuscript.

REFERENCES CITED

ALDEN, W. C. (1928) Landslide and flood at Gros Ventre, Wyoming: Am. Inst. Min. Met. Eng. Trans., vol. 76, pp. 347–361.

BLACKWELDER, E. (1928) Mudflow as a geologic agent in semiarid mountains: Geol. Soc. America Bull. 39, pp. 465–480.

BRETZ, J H. (1935) Physiographic studies in East Greenland; in: BOYD, L. A., The fiord region of East Greenland: Am. Geog. Soc. Spec. Pub. 18, pp. 159–245.

CAMPBELL, M. R., *et al.* (1925) Geologic map of Wyoming: U.S. Geol. Survey, Geologic Atlas of the United States.

CONWAY, W. M. (1893) Explorations in the Mustagh or Karakorum Mountains: Geog. Jour., vol. 2, pp. 289–299.

DENSON, N. M., and BOTINELLY, T. (1949) Geology of the Hartville uplift, eastern Wyoming: U.S. Geol. Survey Oil and Gas Inv. Prelim. Map 102.

KRUMBEIN, W. C. (1942) Flood deposits of Arroyo Seco, Los Angeles County, California: Geol. Soc. America Bull. 52, pp. 1355–1402.

LOVE, J. D.; DENSON, N. M.; and BOTINELLY, T. (1949) Geology of the Glendo area, Wyoming: U.S. Geol. Survey Oil and Gas Inv. Prelim. Map 92.

PACK, F. J. (1923) Transportative potential of desert waters: Pan.-Am. Geologist, vol. 40, pp. 349–356.

SMITH, W. S. T., and DARTON, N. H. (1903) Geologic map in Hartville folio: U.S. Geol. Survey, no. 91.

SPENCER, A. C. (1916) The Atlantic Gold District and the north Laramie Mountains: U.S. Geol. Survey Bull. 626, pp. 47–85.

STOSE, G. W., assisted by LJUNGSTEDT, O. A. (1932) Geologic map of the United States: U.S. Geol. Survey.

TROWBRIDGE, A. C. (1911) The terrestrial deposits of Owens Valley, California: Jour. Geology, vol. 19, pp. 706–747.

WOODFORD, A. O. (1925) The San Onofre breccia; its nature and origin: Univ. California Dept. Geol. Sciences Bull., vol. 15, pp. 159–280.

WORCESTER, P. G. (1939) Textbook of geomorphology, New York, D. Van Nostrand Co., Inc.

GEOLOGICAL NOTES

IMPROVED EQUIPMENT AND TECHNIQUES FOR ORIENTATION STUDIES OF LARGE PARTICLES IN SEDIMENTS[1]

THOR N. V. KARLSTROM
U.S. Geological Survey, Washington, D.C.

INTRODUCTION

Improved equipment and techniques for studying the orientation of large particles in sediments have been developed. These may encourage extended use of sedimentary fabric studies as a field and research procedure. A template and a goniometer were constructed recently by the United States Geological Survey, and modified laboratory and field procedures were developed.

The equipment and techniques have been applied successfully to pebble and cobble samples, most samples containing more than 100 particles, collected from glacial till, frost-disturbed sediment or congeliturbate, and other unconsolidated deposits of the Kenai Lowland area, Alaska. Studies were made in connection with the program of the Alaska Terrain and Permafrost Section, United States Geological Survey. Fabric studies of isolated exposures of till have permitted a direct determination of the direction of glacier movement, not otherwise evident, and have assisted correlation and mapping of glacial deposits. Orientation studies of particles in congeliturbates have yielded quantitative data bearing on frost processes. Similar studies are being applied to samples collected from various other types of sediments and should assist in classification and understanding of both depositional and postdepositional processes. Previous studies by Richter (1932), Miner (1934), Fraser (1935), Wadell (1936), Cailleux (1938), Krumbein (1939, 1940, 1942), Holmes (1941, 1949), and Lundqvist (1949) have established the value of such studies as an important research tool directed toward problems of sedimentation.

The method of sampling and analysis is based on that developed by Wadell (1936, pp. 76–79) and elaborated by Krumbein and Pettijohn (1938, pp. 270–272, 274). However, the improved instruments described here permit more rapid and convenient sampling and laboratory analysis than were possible heretofore. In addition, new techniques, employing inexpensive and readily available equipment, permit the geologist to complete orientation analyses in the field, thus minimizing transportation and storage of bulky samples. These techniques also may be applied in the laboratory by students and others unable to obtain specialized and expensive equipment.

Three main steps are required to study orientation of large particles in sediments: (1) a large number of particles[2] are marked in outcrop so that their spatial attitudes can be duplicated; (2) after removal from outcrop, the particles are reoriented, and the critical parameters, such as axes and faces, are measured; (3) the parameter data are presented in a form permitting statistical analysis of preferred orientation for each sample. By the method employed, each particle is marked by projecting a vertical and a horizontal line onto the exposed surface of the particle and placing a dot to indi-

[1] Manuscript received February 16, 1952.

[2] The number of particles required for each orientation sample must be large enough to permit significant statistical results. Samples containing 100 or more particles are considered adequate for the purposes of most studies. Holmes's study (1941, p. 1308), however, indicates that 50 particles from till are sufficient to determine statistically the direction of ice movement.

cate top and bottom. Owing to the irregular surface of the particle, the projected lines appear straight and at right angles only when the particle is viewed from one direction. Proper reorientation of the particles for measurement of parameters is therefore possible because of this line relationship and the marked position of top and bottom. The present discussion is limited to a description of equipment and techniques relating to marking and reorienting particles and measuring their parameters. Methods and examples of data presentation are discussed by Krumbein and Pettijohn (1938, pp. 182–211, 272–274), and Pettijohn (1949, pp. 61–62). Contour and rose diagrams are probably the most useful of these methods for visualization and interpretation of orientation patterns.

NEW INSTRUMENTS

An orientation template was designed to expedite marking of the particles in the field, and an orientation goniometer was developed to facilitate orientation and measurement of the marked particles after removal from outcrop. Both instruments were constructed by the U.S. Geological Survey according to designs submitted by the author.

ORIENTATION TEMPLATE

The orientation template is a 4×4-inch lucite plate, $\frac{1}{4}$ inch thick, in which two slots $\frac{3}{8}$ inch wide are cut in the form of a cross (fig. 1). An inset bubble level permits leveling of the plate. When the plate is held vertically and in the level position, one of the slots is horizontal, the other vertical. The slots are just wide enough to permit the marking pencil to slide freely with a minimum of lateral freedom. The red T. Blaisdell china-marking pencil No. 169 was found most suitable for use on wet or dry, dirty, and irregular particle surfaces; the marks are sufficiently durable to permit the necessary transportation of particles in bags without obliteration of lines.

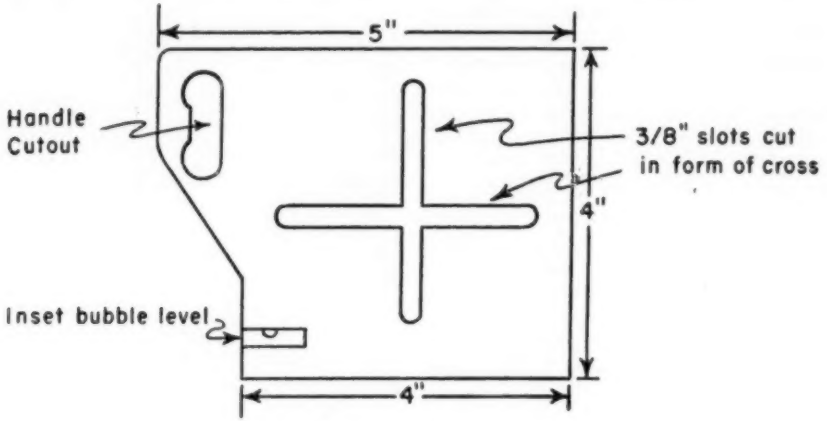
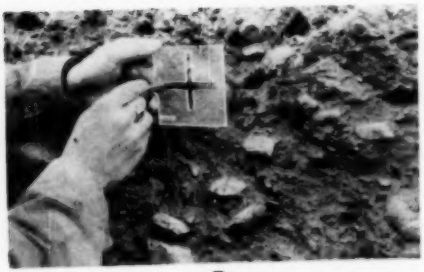


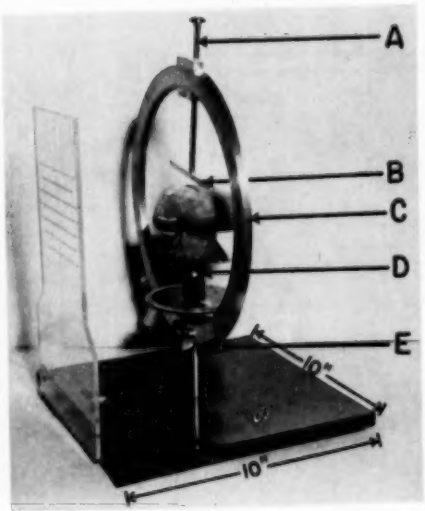
FIG. 1.—Orientation template

The marking procedure with the orientation template is simple and relatively rapid: (1) Prepare a straight vertical face on the exposure and record its bearing. (2) Expose and prepare surfaces of particles to be marked, being careful not to jostle particles out of position in matrix (pl. 1, *A*). (3) Level orientation template in front of particle, parallel to outcrop face, and mark particle by guiding pencil along the template (pl. 1, *B*). The pencil must be held as nearly perpendicular to the template as possible. (4) Place a dot on the particle to indicate top

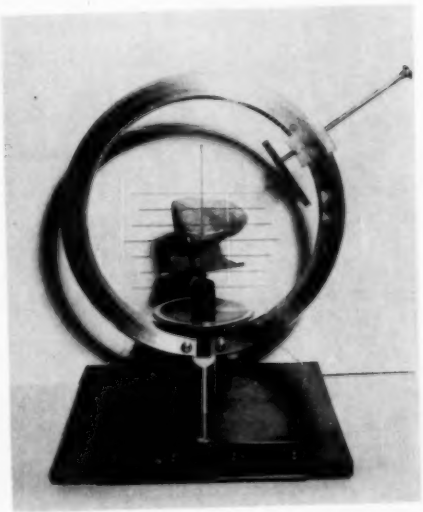
A



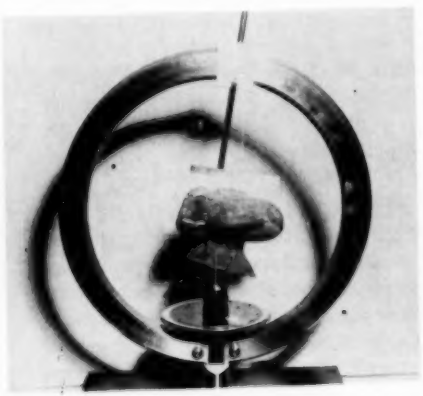
B



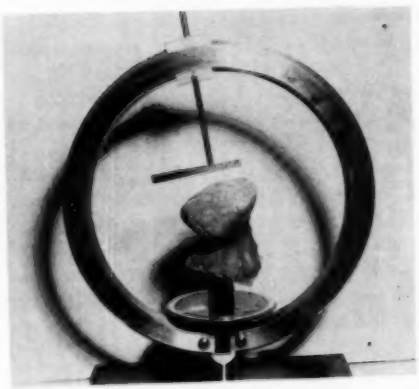
C



D



E



F

Orientation template and goniometer

or bottom before removing from outcrop. Arbitrarily, the dot was always placed in the lower left quadrant made by the lines marked on the particles.

The marked particles can be properly reoriented, either by the use of the orientation goniometer or by a procedure employing less specialized equipment. Lines on the particles should be drawn as long as possible, for accuracy in orientation. Particles marked on strongly curved surfaces or across two or more faces are most readily oriented, because the resulting lines are most irregular in trend except when viewed from the proper direction. Before analysis with the orientation goniometer, lines may be painted and the particles numbered with quick-drying enamel to insure permanence and to facilitate handling.

ORIENTATION GONIOMETER

The orientation goniometer (pl. 1, *C*) is basically a large two-circle contact goniometer to which has been added a small mounting stage and an adjustable, detachable transparent plate inscribed with a vertical line and a set of horizontal lines. The mounting stage is set on a ball-and-socket joint at the center of the horizontal circle (a microscope stage was used for the horizontal circle); the transparent plate is mounted on the goniometer base parallel to the vertical circle. The horizontal circle is graduated from 0° to 360°; the vertical circle from 0° to 100° from the top down on both sides. The inside dimension of the vertical circle is 8½ inches and is large enough to handle pebbles and most cobble-size particles. The combination of the adjustable inscribed lucite plate and the ball-and-socket mounting stage permits rapid orientation of the particles by eliminating the need to adjust the particles in the modeling clay after they have been mounted. The horizontal-circle index is so placed that true bearings of reference lines in the particles may be read directly from the scale. Plunge of linear parameters and dip and strike of prominent particle faces are obtained by use of a goniometer ruler mounted on the vertical circle. The procedure of orientation and measurement of particles with the goniometer is as follows:

1. Set horizontal-circle index at the bearing of the outcrop face from which the particle was taken and lock in position by turning knurled knob at back of support stem (the stage lock, pl. 1, *C*). As the same adjustment is required for each particle during the running of a sample, it has been found convenient for ease of reference to mark with a paper tab the bearing of the outcrop face on the stage.

2. Orient particle by mounting firmly, bottom down, in modeling clay on mounting stage, and, while looking through inscribed lucite plate, move mounting stage on ball-and-socket joint so that lines on particle are coincident with lines on lucite plate (pl. 1, *D*). After particle is oriented, unlock horizontal circle. The lucite plate can then be detached from the goniometer to facilitate the measurement of parameters.

3. Measurement of but two parameters, the long and short axes, uniquely determines particle attitude and is sufficient for most orientation studies (Krumbein, 1939, p. 677). However, measurement of other parameters, readily done with the orientation

---

PLATE 1

A, Preparing particles in outcrop face prior to marking.

B, Orientation template shown in proper position for marking particle in outcrop.

C, Side view of orientation goniometer. A, Goniometer ruler; *B*, shoe of goniometer ruler; *C*, vertical circle; *D*, ball-and-socket mounting stage; and *E*, stage lock knob.

D, Orientation goniometer with oriented particle.

E, Particle (same as in *D*) shown in position for measurement of bearing and plunge of long axis.

F, Particle (same as in *D*) shown in position for measurement of bearing and plunge of intermediate axis.

goniometer, may significantly enlarge the scope and accuracy of interpretation.

Axes and other linear elements, such as striae and traces of internal structures, are measured by swinging them into the plane of the vertical circle by rotation of the horizontal circle and reading bearings directly from the horizontal scale. Measure plunge by adjusting shoe of goniometer ruler parallel to linear element in the plane of the vertical circle and reading the angle from the vertical scale. Note direction of plunge. Plate 1, *E* and *F*, shows particles in position for measurements of bearing and plunges of long and intermediate axes.

The strike of a prominent particle face is measured by setting the goniometer ruler at zero index (located at the top of the vertical circle) and rotating the horizontal circle so that a direction on the face lies parallel to the shoe of the goniometer ruler in the plane of the vertical circle. The horizontal index then records the strike of the face. The dip of the face is obtained by rotating the horizontal circle 90° and setting the shoe of the goniometer ruler parallel to the face in the plane of the vertical circle. Read degrees of dip from vertical-circle scale and note direction of dip.

Faces and linear elements on the bottom portion of the particle are measured by reorienting the particle in the upside-down position and correcting for the observed directions of inclination below the horizontal. Owing to the inverted position of the particle, the direction of inclination of a measured element will be the opposite of that observed, but the amount of inclination and the bearing will be the same.

The orientation goniometer permits more rapid analysis and somewhat greater accuracy than is possible with previously designed instruments. The degree of accuracy of parameter measurements is limited mainly by errors inherent in the marking procedure, in the determination of exact positions of parameters in irregular-shaped solid particles, and, to a lesser degree, in the reorientation procedure. The alignment of the orientation template parallel to the outcrop face, the position of particle parameters, and reorientation are determined visually, not mechanically, and errors in resulting parameter measurements may be of the order of a few degrees. These errors however, are random, not cumulative, and in sufficiently large samples they do not significantly affect the results of the analysis.

METHODS OF ORIENTATION ANALYSIS WITHOUT ORIENTATION GONIOMETER

Analyses of particles marked with the orientation template have been made in a field laboratory by employing a few inexpensive and easily constructed items of equipment. These are (1) an improvised clinometer made of a straightedge, protractor, and plumb bob; (2) a circle marked off into 5° arcs drawn on a piece of paper, cardboard, or any available flat surface; (3) a lump of modeling clay mounted on a small square of paper or cardboard; and (4) a transparent plate upon which a vertical line and horizontal lines are drawn. The procedure of analysis is essentially the same as with the orientation goniometer and is illustrated in figure 2. The marked particle is placed in the modeling-clay mount at the center of the circle. The inscribed transparent plate is placed parallel to the bearing of the outcrop face, as marked on the circle. Orientation of the particle is made by adjusting the particle in the mount so that lines on the particle coincide with lines on the plate when viewed from the front. Bearings of axes and other linear elements of the oriented particle are obtained by visually noting where extensions of these elements intersect the arc of the circle. Plunge of axes and strike and dip of prominent faces are then measured by using the improvised clinometer.

A simplified variation of this method permits convenient analysis in the field immediately after collection of the sample and requires only a Brunton compass, the orientation template, and a modeling-clay mount.

Each marked particle is oriented in the clay mount by aligning the lines on the particle with the slots of the orientation template, which has been leveled and held parallel to the compass bearing of the outcrop face. The bearings and inclinations of the parameters of the oriented particle can then be measured directly by Brunton compass.

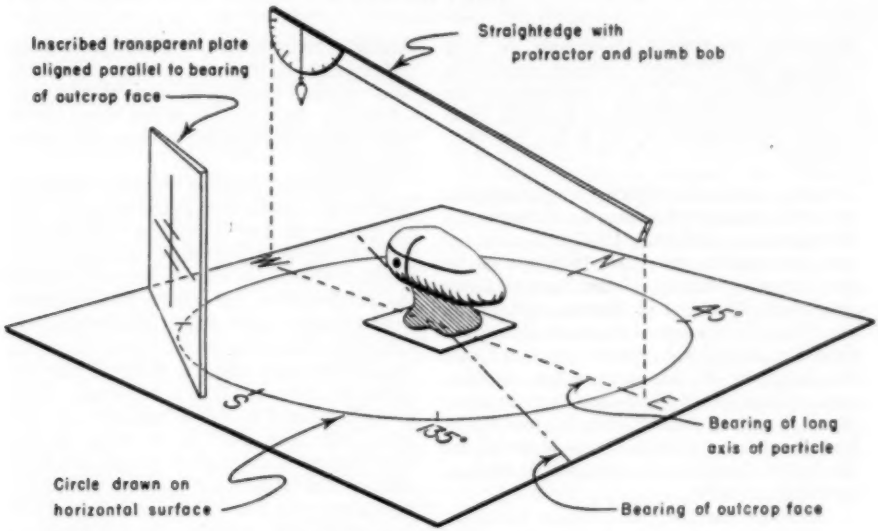


FIG. 2.—Equipment for orienting and measuring parameters of marked particles without orientation goniometer. Clinometer held in position to measure east-west bearing and 30° plunge to east of long axis.

REFERENCES CITED

CAILLEUX, A. (1938) La Disposition individuelle des galets dans les formations détritiques: Rev. géographie phys. et géologie dynamique, vol. 11, pp. 171–198.

FRASER, H. J. (1935) Experimental study of porosity and permeability of clastic sediments: Jour. Geology, vol. 43, pp. 910–1010.

HOLMES, C. D. (1941) Till fabric: Geol. Soc. America Bull. 52, pp. 1299–1354.

——— (1949) Glacial erosion and sedimentation: *ibid.*, Bull. 60, pp. 1429–1436.

KRUMBEIN, W. C. (1939) Preferred orientation of pebbles in sedimentary deposits: Jour. Geology, vol. 47, pp. 673–706.

——— (1940) Flood gravel of San Gabriel Canyon, California: Geol. Soc. America Bull. 51, pp. 639–676.

——— (1942) Flood deposits of Arroyo Seco, Los Angeles County, California: *ibid.*, Bull. 53, pp. 1355–1402.

——— and PETTIJOHN, F. J. (1938) Manual of sedimentary petrology, New York, D. Appleton–Century Co., Inc., 549 pp.

LUNDQVIST, G. (1949) Orientation of block material: Geog. Annaler, vol. 31, pts. 1–4, pp. 335–347.

MINER, N. A. (1934) Talus slopes of the Gaspe Peninsula: Science, new ser., vol. 79, pp. 229–230.

PETTIJOHN, F. J. (1949) Sedimentary rocks, New York, Harper & Bros., 526 pp.

RICHTER, K. (1932) Die Bewegungsrichtung des Inlandeises, rekonstruiert aus den Kritzen und Längsachsen der Geschiebe: Zeitschr. Geschiebeforschung, vol. 8, pp. 62–66.

WADELL, H. (1936) Volume, shape, and shape-position of rock fragments in open-work gravel: Geog. Annaler, vol. 1, pp. 74–92.

REVIEWS

"Zagadnien stratygrafii plejstocenu na Niza Europejskim" ("Some Problems concerning the Stratigraphy of the Pleistocene of the European Lowland.") By B. HALICKI. (*Acta geol. Polonica*, vol. 1, no. 2, pp. 106–142.) 1950.

Among the papers planned for presentation at the Congress of the International Association on Quaternary Research (INQUA) at Budapest, Hungary, in September, 1949, was one by Dr. Bronislaw Halicki, of the Museum Ziemi (Geological Museum) of Warsaw, Poland, on the Pleistocene history of the vegetation of Poland. Dr. Halicki was formerly connected with the University of Vilna and has done considerable research on the Pleistocene. A preliminary report, based on studies on the Niemen Basin, had already been presented at the International Geological Congress in London in 1948 (Halicki and Halicka, 1950).

Although the INQUA congress was postponed, I was fortunate in receiving invitations to field conferences from several Pleistocene geologists in Europe, among them Dr. Halicki. While my stay in Poland was limited to only a few days, I did have the opportunity of discussing various problems of Pleistocene correlation with Dr. Halicki and of taking several short field excursions in the vicinity of Warsaw and Poznan.

It was, therefore, with considerable interest that I recently received a copy of this latest work of Halicki on the Pleistocene of Poland, based primarily on a study of pollen and other plant remains. The conclusions were based upon his own work, especially in the Niemen Basin (former Polish territory, now part of Soviet Lithuania), as well as upon the work of other European geologists. Although the paper has an English summary, it is feared that it may not come to the attention of many American students of the Pleistocene. It has therefore been thought desirable to publish this somewhat extended review at this time.

According to Halicki, three interglacials have been demonstrated that have a consistent aspect over wide areas. The last (V) and penultimate (IV) interglacials represent an eastern facies extending far westward. The antepenultimate (III) interglacial stage, on the other hand, contains western (Atlantic) elements of flora, a result of the moist climate of the time. Less is known about the correlation of the two earlier interglacials.

Halicki points out that the floral differences between the various interglacial stages in western Europe are more difficult to determine because of the oceanic climate of the region. The forests of central and eastern Europe registered the fluctuations of the climate more precisely.

Six different major glacial advances are recognized in Poland as contrasted to four in the Alps and in North America. However, this may not be so unreasonable as it first seems. It was formerly believed that there was only one glaciation older than the Central Polish Boulder Clay. However, the work in the Niemen Basin and in middle Poland has demonstrated two independent older tills (= moraines in the European sense) and a still older residual horizon of boulders of local and Scandinavian origin. This old glaciation may not be represented in the Alps or in America, or possibly evidence for it may be buried. It is also possible that this old glaciation may have been contemporaneous with the pre-Günz gravels of the Alps. Or there may be difficulty in properly correlating the early Pleistocene partly because of confusion between interglacials and interstadials.

The paper gives an extensive bibliography of 110 titles, covering various phases of the European Pleistocene. There is also a map showing the limits of the glacial stages of the European lowland, as well as three excellent tables summarizing the characteristic deposits, flora and fauna, and correlation of the Polish Pleistocene.

The reviewer has attempted below to summarize the more important data contained in these tables. In some cases he has added some information or suggestions based upon personal conversation and correspondence with Halicki. When such information is not to be found in the printed report, it is included in brackets. This is particularly true in regard to the tentative correlations with the North American glacial chronology.

Preglacial.—No Baltic Sea in existence; highly weathered river gravels from Scandinavia and local sources. Peat beds in river sands in Pruzana. Pollen indicated a pine-birch forest with some alder and fir and possibly hemlock (*Tsuga?*). Macroscopic remains include *Pinus silvestris, Quercus* sp., *Carpinus betalus* (beech), *Populus* (poplar), and *Juniperus communis* (juniper).

1st glacial (*Old Glacial*).—Extended to central Poland and possibly beyond, exact limits not certain; only resistant rocks preserved as "boulder pavement." Rocks derived from Scandinavia, in many cases weathered and impoverished. Probably equivalent to the Jaroslavien or Icenien in Poland (Szafer, 1946) and to the lower marine Pleistocene of Germany and Holland, with a boreal arctic fauna. [May be pre-Nebraskan of the U.S.A. and equivalent to the pre-Günz gravels of the Alps.]

1st interglacial (*Wilno*).—Of very long duration. River sands and silts with mollusks and plant remains. Flora from boring near Wilno (Vilna) includes wood of oak (*Quercus*), pine (*Pinus*), and alder (*Alnus*). Equivalent to the Sandomirien or Cromerien (Szafer, 1946) and probably has both marine and nonmarine equivalents in Germany and Holland.

2d glacial (*Carpathian*).—Extended to the Carpathians in southern Poland, contains the oldest well-preserved boulder clays. Probably synonymous with the Cracovien (or Saxonien) of Szafer, equivalent to the Elster of Germany and Holland, the Lichvin of the U.S.S.R., Moraine A of Denmark [and possibly the Nebraskan of the U.S.A.].

2d interglacial.—Extensive peat and lake deposits on the Niemen River. On the basis of the pollen, it can be established that there were two phases of oak and elm, separated by a slightly cooler phase. Macroscopic plant remains from this interglacial include the Siberian spruce (*Picea obovata*). The fauna includes rhinoceros bones and a fresh-water mollusk assemblage (unfortunately lost during the war). Contained a warm, largely continental association, possibly equivalent to the Esjberg clays (cool phase) and the *Tellina* clays (warm phase) of Denmark, part of the Elster/Saale interglacial deposits of Germany [and possibly those of the Aftonian of the U.S.A.]. [This probably equals the "Great Interglacial."]

3d glacial (*South Polish*).—Extended to southern Poland; boulder clay; distinct glacial forms lacking; also varved clays and loess. Equivalents outside Poland uncertain. [May equal Kansan of the U.S.A.]

3d interglacial.—Mixed forests with a cold stage near the end. "Coniferous forests prevailing in the whole profile (*Pinus, Picea, Abies, Larix*). The lower climatic optimum warmer than the upper. In both, a separate deciduous forest zone is lacking." This stage is well shown on the Niemen River, as well as at several places in middle Poland. It is referred to the Masovien I or Dürnterien of Szafer (1946). Other probable equivalents of this stage are the upper horizons at Spannenburg and Bergumerheide and the Neede horizon in Holland, the *Paludina* horizon at Berlin, and the Holstein sea in Germany. More distant correlations may be the pre-Dnieper interglacial at Lichvin in the U.S.S.R. [and possibly the Yarmouth of the U.S.A.].

4th glacial (*Central Polish*).—Extended to the southern part of middle Poland. The first glacial zone with well-preserved forms (terminal moraines, eskers). "It is probably connected on the east with the Dnieper glaciation and on the west with the Saale glaciation." Halicki suggests a correlation with the Saale plus Warthe on his Chart 3. Equals Varsovien I or Polonien of Szafer and probably part of the Riss of the Alps, Moraine B of Denmark [and the Illinoian of the U.S.A.].

4th interglacial (*Eemian*).—Peat bogs and lakes with extensive flora. Equivalent to the Eem interglacial, as well as to the lower part of the Herning peat beds of Scandinavia; also equals the Riss/Würm of the Alps [and probably the Sangamon of the U.S.A.; marine sediments with Eem fossils have recently been found near Tychnowy in Pomerania].

5th glacial (*North Polish*).—Extended to the northern part of middle Poland; well-preserved glacial forms, such as end moraines, drumlins, eskers, etc.; "older loess." [Equals the Würm I of the Alps, Moraine C of Denmark, and possibly the Iowan of the U.S.A.]

5th interglacial (*Aurignacian*).—Forest evolution from cool base to cool top separated by oak-mixed forest, with oak and elm dominant; very extensive flora; fresh-water mollusks. Probably contemporaneous with the Aurignacian interglacial, the Skaerumhede marine fauna of Denmark, as well as the upper part of the Herning peat beds, the Würm I/II of the Alps [and possibly the Peorian of the U.S.A.].

6th glacial (*Baltic*).—Covered northern Poland; represented in the south by the "younger loess"; forms very fresh. Separated into the fol-

lowing: (*a*) Brandenburg-Leszno substage; (*b*) possibly an interstadial (Szafer placed the Aurignacian interstadial here, but Halicki places it in the 5th interglacial); (*c*) Poznanian substage; (*d*) Masurian interstadial; and (*e*) Pomeranian substage. Equals Varsovien II or Vistulien (Szafer, 1946), the Würm II and III of the Alps, Moraines D–H of Denmark, the Waldai stage of the U.S.S.R. [and probably the various substages of the Wisconsin younger than the Peorian of the U.S.A.].

Another possible correlation would be to regard the "old" glaciation as equivalent to the Nebraskan, and the Wilno interglacial as the Aftonian. Then the Carpathian and South Polish might equal the Kansan, with an interstadial between them. Or the Wilno might be the interstadial, and Halicki's 2d interglacial (with its fluctuation in climate) might be equivalent to the Aftonian and the Günz/Mindel. Or Halicki's stage between the South Polish and Central Polish may be interstadial rather than interglacial.

It is, of course, dangerous and premature to offer a positive correlation of the glacial chronology over such great distances, and Halicki is undoubtedly wise in not publishing a complete correlation table. Any correlations earlier than the South Polish glacial stage are regarded as highly tentative.

REFERENCES CITED

HALICKI, B., and HALICKA, A. (1950) La Stratigraphie du Quaternaire dans la Bassin du Niemen: 18th Internat. Geol. Cong. Proc., pt. 9, pp. 47–53.

SZAFER, W. (1946) Zarys historii rozwuju flory Holarktydy: Rocznik Polskiego Towarzystwa Geologicznego, vol. 16, pp. 177–242.

HORACE G. RICHARDS

Academy of Natural Sciences of Philadelphia

Il Pliocene e il postpliocene dell'Emilia. By G. RUGGIERI and R. SELLI. (Reprinted from *Gior. Geologia, Annali Mus. Geol. Bologna*, ser. 3, vol. 20.) 1948.

This paper will interest a large number of students, because it deals with the stratigraphy of a type series of the Pliocene and post-Pliocene. Therefore, a summary, rather than a review, is presented here.

PLIOCENE

Although the Pliocene section in Emilia, northern Italy, is considered the type for this period, at least for the Mediterranean Basin, it has been often misinterpreted.

The Pliocene began with a general marine transgression marked in the sub-Apennines by an angular unconformity. Sediments are generally clays, and a basal conglomerate is rarely present. The Pliocene is cut at different places by the Calabrian or Milazzian transgressions or by Recent alluvial terraces.

Lower Pliocene (*Tabian of Doderlein and Cocconi*).—This epoch is generally represented by clays, but in the infra-Apenninic basin south of Bologna these grade southward into sandy clays, molasse, and conglomerates. The Lower Pliocene and Upper Miocene faunas are so similar that distinction between these series is possible only when the dividing unconformity can be located. This is also true elsewhere in Italy and in Albania.

Middle Pliocene.—Diastrophic activity took place at the beginning of this epoch. The sea bottom emerged at a few places (Castrocaro), while at others the water became shallower (Castellarquato) or deeper (provinces of Bologna and Forlì). Eopliocene species were replaced by new species.

Upper Pliocene.—Emergence continued regularly in the western part of Emilia and characteristic deltaic sediments were deposited (Castellarquato). Deep-sea sedimentation continued to the east (Forlì), but in some areas (Bologna) sedimentation ceased. This may have resulted from a local earlier beginning of the post-Pliocene marine regression or from Calabrian erosion. In this epoch some new species appeared, and at its end many older species became extinct.

Typical localities of the different epochs are:

Lower Pliocene: Tabiano and Maiatico (Parma).

Middle Pliocene: (*a*) deep facies: Ponticello di Savena (Bologna); (*b*) medium-deep facies: S. Maria Maddalena (Castellarquato); (*c*) calcareous organic facies: Castrocaro (Forlì).

Upper Pliocene: Rio Riorzo (Castellarquato) and Capocolle (Forlì), both littoral.

PLEISTOCENE

The thickness of the Pleistocene marine sediments, mostly clays, varies from a few tens of meters above the buried hills of the Po

Valley to 600 meters in the Polesine area and 800 meters near Imola. The sedimentary column may be divided as follows:

Zone A.—Marine clays deposited at moderate depth, lying unconformably upon Tertiary sediments. Sometimes these clays possess a basal conglomerate with reworked Pliocene fossils and an angular unconformity. More often transitions occur, and distinction between the two series can be made only through their faunas. The typical macrofossil is *Cyprina islandica*. Microfaunas are rich and characterized by few Pliocene forms, some of which lived at greater depth during that epoch, and several North Atlantic immigrants.

Zone B.—Marine clays, mostly deposited in shallow water, with microfaunas very poor in number of species (15–20 species).

Zone B_1.—Marine sandy clays deposited in shallow water with microfaunas somewhat richer than in zone B (30–35 species), without North Atlantic immigrants, and similar to the present North Adriatic microfaunas.

Zone C.—Sandy clays and clayey sands with microfaunas similar to those in zone B, but also with many species typical of zone A.

Zone D.—In the Po Valley: clayey sands and sandy clays, with microfaunas similar to zone C but indicating somewhat warmer conditions. In the sub-Apennines: transgressive yellow sands with mollusks, *Elephas*, *Hippopotamus*, *Bos*, etc. In the Po Valley, alternating marine and deltaic sediments occur in the upper part of zone D. These grade upward into Recent continental sediments.

The Pleistocene marine system is complete, or nearly so, in many areas of the Po Valley (Polesine, etc.) and in the sub-Apennines between Castel S. Pietro and Forlì. In these areas it constitutes half to two-thirds of the entire post-Pliocene column. In other areas, one zone or another zone may be absent.

The relations between the different zones and epochs, and their correlation with the continental Pleistocene is indicated in the accompanying table.

Zone	Epoch	Climate	Correlation with Continental Pleistocene
D.....	Milazzian	Warmer	Mindel-Riss
C.....	Sicilian	Colder	Mindel
B_1.....	Emilian	Warmer	Günz-Mindel
A, B....	Calabrian	Colder	Günz

The new name "Emilian" is proposed for the warmer epoch following the Calabrian.

The Pleistocene system of northern Italy shows no evidence of extensive alternating emergence and submergence corresponding to glacial stages. Only moderate variations in the sea depth and a minor submergence at the beginning of the Milazzian are evident.

Early Calabrian submergence was undoubtedly tectonic. In some areas this commenced slightly before the beginning of the first glaciation and the early sediments lack North Atlantic immigrant *Foraminifera*. Diastrophism again occurred after the Milazzian stage along the margin of the sub-Apennines, where Milazzian yellow sands were raised about 300 meters.

CESARE EMILIANI

University of Chicago

Tunnelbaugeologie: Die geologischen Grundlagen des Stollen- und Tunnelbaues. By JOSEF STINI. Vienna: Springer-Verlag, 1950. Pp. 366; figs. 192. $8.80.

Josef Stini, the well-known author of *Ingenieurgeologie* (1924), *Technische Gesteinskunde* (1926), and *Die geologischen Grundlagen der Verbauung der Geschiebeherde in Gewässern* (1931), has now prepared another publication in the field of engineering geology, *Tunnelbaugeologie*.

The author begins with the preliminary investigations to be done by the geologist in the office and in the field. The first chapter outlines the methods that are used to loosen and blast the rocks and that are both most efficient and safest for the workers involved. These objectives are gained by taking advantage of the rock structures. In some cases the geothermal gradient has been a severe handicap to successful tunnel-driving. The methods of temperature prediction are explained.

In the following chapter the influence of rocks and rock structures on the distribution and circulation of ground water is described in detail. The effects of acidic and alkalic waters on the cement of the tunnel lining are included.

The chapter on rock pressure and its effect on hollow tubes is based on careful investigations both in the field and of the literature. The author has previously published a classical study on rock pressure in his own journal,

Geologie und Bauwesen. Stini's classification follows:

1. Static rock pressure; active movement only if the equilibrium is destroyed by tunneling; pressure by overload of rocks overlying the tunnel, including water pressure
2. Dynamic rock pressure
   a) Sliding pressure on valley slopes
   b) Rock pressure in a narrower sense, mountain-building pressure, tectonic pressure
   c) Pressure caused by chemical changes of rocks
   d) Pressure due to rock disintegration caused by careless blasting

All Stini's experience is based on tunneling in the complicated rock structures in the eastern Alps. The influence of the coherence and consistency of rocks on the phenomena of deformation under pressure, which is as important as the rock pressure itself, is likewise analyzed in the same chapter on rock pressure. There is a classification of rock resistance in eight stages ranging from solid rock to rocks of flowing consistency. The problems of tunnel-driving in each stage are outlined.

Heavy bombardment of the war plants in Germany required their transfer underground. A new field of engineering was thus opened up. The thickness of the supporting pillars and the allowance of open space had to be determined with regard to the rock structures and the competence of rocks. The last chapter, devoted to this subject, includes consideration of air-raid shelters, high-pressure tunnels, and excavations for subterranean powerhouses.

An appendix contains a good description of the latest American tunnel-driving methods. A carefully compiled international bibliography is attached to each chapter. The reader will be very much amazed at Stini's exhaustive knowledge of the international literature. More photographs and drawings would have improved the author's presentation, especially in the field of rock pressure. No doubt general postwar financial difficulties in Europe did not allow better illustrations.

Stini's language is clear; the American reader, however, may stumble over some Germanizations of international scientific terms. A good balance between technical details and the geological problems has been achieved. Many examples taken from his experience and illustrated with fairly good drawings are helpful. It should be translated and be considered the handbook for the engineering geologist and the tunneling engineer. We thank Professor Stini for this excellent publication, for which a true need existed.

ERHARD M. WINKLER
University of Notre Dame

Conservation of Natural Resources. Edited by GUY-HAROLD SMITH. New York: John Wiley & Sons, Inc.; London: Chapman & Hall, Ltd., 1950. Pp. xii+552; figs. 164. $6.00.

Conservation of natural resources has high priority today in the minds of thoughtful citizens, whose number is greater, I suspect, than the pessimists will admit. But the problem is how to get on with conservation. Education is almost invariably cited as a strategic approach, and so it should be. But, if the experience of this writer is any criterion, a lot of education is going on—going on to the point where people are stirred up. There it stops, leaving ing its victims like swarming bees without a queen.

Nothing would be pleasanter than to be able to say that the excellent and impressive book listed above ushers in a new era in conservation education, giving not merely a sense of crisis but a sense of direction to its readers. Certainly all praise is due an editor, who, in addition to writing four out of twenty-three chapters, has been able to enlist nineteen collaborators, all competent and many eminent, in a joint enterprise.

As matters stand, *Conservation of Natural Resources* can be recommended as a mine of information about all types of resources, renewable and nonrenewable. More than that, certain chapters suggest concrete measures to be taken; others in troubled honesty (as, for example, the chapter on conservation in the mineral kingdom) set forth dilemmas to which no one as yet has the answer. But too many, in my judgment—which, God knows, is highly fallible—seem somehow glibly to pass the buck with generalities about federal agencies, regional planning, and the like.

There is a hard core of solid principles underlying the problem of conservation. There is also a respectable source of guidance toward practical action for every citizen. Much of this latter is empirical and intuitive. But even more of it is rooted in the amazing advances of cultural anthropology and group psychology. Without for a moment discounting the importance of resource inventories and warnings,

we all need, I think, to learn what needs to be done and how we can go about doing it, under our existing political, economic, and social philosophy.

PAUL B. SEARS

Yale University

Igneous and Metamorphic Petrology. By FRANCIS J. TURNER and JEAN VERHOOGEN. 1st ed. New York: McGraw-Hill Book Co., Inc., 1951. Pp. ix+602; figs. 92. $9.00.

This is a welcome text "intended for the use of advanced students, research workers, and teachers in the field of petrology." It views the science as based on physics and chemistry and attempts to set forth the fundamental principles of these basic sciences applicable to the crystalline rocks and to weave the applications into the natural history of the rocks, to which end the authors represent an admirably constituted team.

The principles of chemical equilibrium are discussed in a chapter of some forty pages. To a degree this chapter stands apart from the rest of the subject matter. The authors refer a few times in later chapters to principles here developed, but not so often as a devotee could wish. No criticism of the authors is intended in this statement. The condition is rather a reflection of the state of development of our science and of the difficulty of applying the principles to situations of the extreme complexity of natural processes and their products. The gap will gradually be bridged as more petrologists master fundamental theory. As of now, most petrologists will find a good deal of the material of this chapter beyond them, and perhaps no petrologist could claim complete mastery of it. Nevertheless, it is an end toward which we should strive.

The aspects of chemical equilibrium discussed are well chosen. In some places utility is sacrificed to rigor. Thus on page 28 an assemblage of plagioclase and hornblende is said to be a two-component system if it is assumed that the assemblage can suffer no change. But such an assumption removes the system from the sphere of interest of the petrologist. He wants to know how many components there are if the assemblage may experience one of the many changes which he views in rocks, in which case the number of components may be considerably greater than two.

The authors point out on page 38 what they regard as an exception to Le Chatelier's principle. One wonders whether their view is well taken. Thus they state that if one increases the volume of the system water + vapor, water is vaporized, and the vaporization results also in an increase of volume. "In this case, the change that occurs in the system by changing one of the factors of the equilibrium (volume) is not such as, if it occurred alone, would cause a variation of opposite sign of the factors considered, as stated in Le Chatelier's principle." But volume is an extensive variable, and one can change the volume *qua* volume of either of the phases in the system water + vapor (i.e., one could add a further volume of water or vapor) without changing the equilibrium in any way. It is only when one seeks to change the volume by indirection, viz., by changing the intensive variable, pressure, that the apparent exception to Le Chatelier's principle crops up. No real exception is involved, for the change of volume is always in a direction tending to compensate for the change of pressure.

Mingled with the mathematics of this chapter are many interesting suggestions, as, for example, the explanation offered on page 45 for the fact that reactions take place more readily with rising than with falling temperature, a relation that is particularly well displayed by silicates in the laboratory. This behavior is, of course, fundamental to the preservation in nature of any high-grade mineral assemblages, for the conditions under which we examine the assemblages and under which they have long existed are always low-grade.

In chapter v the authors discuss actual determined equilibria in silicates as distinct from the principles of equilibrium. Here a series of significant equilibrium diagrams is presented, largely diagrams that emanate from the Geophysical Laboratory, with emphasis upon those concerned with rock-forming silicates. The material is well chosen, though it would seem that the chapter could well be expanded. However, these actual examples of silicate equilibria are repeatedly referred to by the authors in other sections of the text, thus proving of greater utility than the theoretical aspects of equilibrium.

Before proceeding to discuss igneous rock series in the light of these diagrams, the authors review certain generalizations that can be drawn from the diagrams, especially the reaction principle of this reviewer and its signifi-

cance in connection with the crystallization differentiation of magmatic systems and the reaction of magma with foreign material.

The discussion of igneous rock associations carries the reader somewhat beyond the middle of the book. The value of having all this descriptive and interpretative material brought together is very great. The authors present without bias the various hypotheses that have been offered in explanation of the several associations. Strong advocacy of any individual hypothesis is studiously avoided, but usually a preference is stated and the reasons for the preference are given. Basaltic magma is accepted as a primary magma, and the great volume of literature on the crystallization of basalt is critically reviewed. The problem of the occurrence of certain associations in connection with certain types of orogeny naturally enters these discussions—indeed, the authors make it a principal feature of their approach, though in part disguised by the use of geographic terms, oceanic and continental.

In giving the various hypotheses that have been offered as to the source of primary basaltic magma, it is stated (p. 194) that, according to this reviewer, "the source of *basaltic* magma in general is a *basaltic* layer of the earth's crust. . . ." Actually, this reviewer has stated his doubts that a basaltic layer could be the source of basaltic magma, the real source, in his view, being stated by the authors in a continuation of the same sentence: "a product of differential fusion of an ultrabasic layer lying beneath."

Of the much discussed question of the origin of alkaline magmas the authors accept no single solution. For the variety of alkaline rock that is quantitatively of greatest significance they say: "Nepheline syenites crystallize from low-temperature residual magmas, the composition of which has been conditioned—in some way not understood—by unusually high concentration of volatile components. More than one mode of origin is probable for such magmas."

The problem of the origin of ultrabasic rocks, and especially of dunite and serpentine, is discussed very fully. The alternatives between which the petrologist must choose are plainly stated—either the intrusion of a wet dunitic magma or the intrusion of a largely crystalline olivine mass. A preference for the latter is indicated, but a wise note of caution is added: "But this, like any other hypothesis, is subject to future modification or rejection should it prove incompatible with facts yet to be discovered."

The origin of granite, to mention only one more of the innumerable problems discussed, is treated at considerable length. They conclude that the great bulk of granite is of magmatic origin. Granitic magma itself they accept as capable of formation by pure differentiation of basaltic magma, but usually assimilation of salic rock has aided the development of such granitic magma. The great batholitic masses of granite (and granodiorite) they regard as formed from magma generated by almost complete fusion of deep-seated rocks. Granitization is considered to be of minor importance in the generation of granite and usually an accompaniment of true intrusion.

After this survey of igneous rocks the authors proceed to discuss the origin and development of magma in the light of present knowledge of the whole earth and its probable history as an astronomic body. Combining this with their petrologic survey, they arrive at three primary magmas—primary olivine basalt magmas, primary tholeiitic magmas, and primary granodiorite-granite magmas—from which all rocks may be derived. The several derivatives are presented in schematic form (p. 366). This choice of primary magmas follows, for the most part, the current vogue.

The reader is now led to a consideration of the metamorphic rocks. Again chemical equilibrium is the dominant fundamental consideration, equilibrium being established (or striven for) in response to changes of temperature, pressure, and stress, on the physical side, and to metasomatism and metamorphic differentiation, on the chemical side.

Equilibrium in metamorphic rocks is treated, for the most part, in the light of Eskola's facies principle, which has been the most fruitful approach to the problems of their origins and classification. The mineral assemblages are thus a response to imposed conditions, and the diagrams of Eskola and others which depict the possible assemblages (and incidentally the impossible ones, at equilibrium) under a variety of conditions are presented and discussed very fully. There is a discrepancy between the statement on page 431, ". . . in the Oslo region . . . cordierite always appears instead of the chemically equivalent pair andalusite-hypersthene," and the statement on page 425, ". . . in the Oslo hornfelses, biotite often appears as a

fourth phase in assemblages such as andalusite-cordierite-hypersthene."

Since one of the principal features of most metamorphic rocks is their deformation, a study of the response of a rock to deformation is a major concern of modern petrology. This has not only physical but also chemical aspects, for it is known that stress may facilitate reactions and it has been supposed that certain phases may form under stress that cannot form in its absence. The authors discuss rather fully this question of stress minerals (and antistress minerals) from both the theoretical and the petrographic viewpoints. They conclude that theory is in conflict with the petrographically established concept of stress minerals. It has usually been supposed that theory rather favors the concept but that under critical petrographic and geologic examination all the so-called "stress minerals," with the possible exception of kyanite, fail to give satisfactory evidence of the stress requirement.

The physical aspects of the deformation of metamorphic rocks as revealed in their fabrics are considered rather fully—indeed, some sixty pages are devoted to a discussion of petrofabrics. This is perhaps the best place to find an evaluation of the general significance of petrofabric studies as distinct from the actual techniques of such studies. The authors are forced to the conclusion: "Until more experimental data are available regarding development of oriented fabrics under controlled conditions, some degree of ambiguity must attend tectonic and kinematic interpretation of schistosity."

In a final chapter the relation between magma, metamorphism, and orogeny is considered. The association of batholithic intrusion with regional metamorphism and alpine folding are noted, and suggestions are offered as to the manner in which metamorphism may pass into magma formation in downfolded belts.

All in all, the authors have covered the petrology of crystalline rocks as thoroughly as it can be done in a single volume. The book is well written, discussion of highly controversial questions is temperate, but there is no hesitation in taking sides where the facts seem to warrant that course. It is a good book. Every petrologist who can borrow $9.00 should have his copy.

N. L. BOWEN

Geophysical Laboratory

The Geology of the Commonwealth of Australia. By T. W. EDGEWORTH DAVID. Edited and supplemented by W. R. BROWNE. 3 vols. London: Edward Arnold & Co., 1950. Vol. 1, pp. 747; figs. 209; pls. 58; tables 28. Vol. 2, pp. 618; figs. 163; pls. 26; tables 7. Vol. 3, Geological Map of the Commonwealth of Australia, 4 sheets, 1:2,990,000, and Geological Sketch Map of Australian New Guinea, 1:2,500,000. $50.00.

For years to come, this monumental work is likely to be the standard reference book on the geology of Australia. The first two volumes embody an immense amount of compilation, description, and discussion, which was begun several decades ago, by Sir Edgeworth David and, after his death in 1934, continued and carried to completion by a large group of Australian geologists, notably Dr. W. R. Browne.

The first volume deals with the stratigraphy of the continent. All systems, from the pre-Cambrian to the Quaternary, are represented. One hundred pages deal with the pre-Cambrian. The earliest, highly metamorphosed gneisses and complexes of crystalline schists are as difficult to correlate in Australia as in all other continents. Two major orogenic episodes—the Pilbaran and Houghtonian—are the basis for subdividing the pre-Cambrian rocks into three general age groups. The great pre-Cambrian platform of central and western Australia is tentatively subdivided into three nuclei along the north coast, two along the northwest and west coast, and possibly a sixth one on the south coast. These are believed to be relatively stable areas, and between them are wide tracts of greater accumulation of sedimentary material (fig. 200, p. 693). This picture resembles in all essential aspects the configuration of pre-Cambrian rocks in the Canadian Shield, southwestern Africa, and Fennoscandia.

As they are widely distributed over the continent, the latest pre-Cambrian formations are described in particular detail. Among them are the famous tillite beds. Late pre-Cambrian rocks are known to attain thicknesses of as much as 30,000 feet, and, according to Sprigg, the tillite beds south of Adelaide, South Australia, are more than 1,200 feet thick, though individual tillites are ordinarily not over 100–200 feet thick. As many as six tillites have been observed in some sections, with which are associated fluvioglacial and lacustrine de-

posits. A line connecting the four principal tillite areas of Australia runs from the northwest coast southeastward to Zeehan Island, Tasmania, and is 2,000 miles long. Some observations suggest that the ice moved from south to north, but the matter is not settled.

The Cambrian rocks of Australia are interesting because in a broad, central belt they appear to have been deposited without sharp break from latest pre-Cambrian sediments. Another, narrow belt, exposed at the east coast is the earliest indication of the great Tasman geosyncline, in which the bulk of the Australian Paleozoic formations were laid down. The chapters on the Ordovician, Silurian, Devonian, and Carboniferous systems, which fill 190 pages of the volume, remind one strongly of the geology of the Appalachian Mountains or the Caledonian-Variscan areas of Europe and Asia Minor. For each system, maps show principal areas of deposition; columnar and cross sections illustrate the sequence and structure of the better-known districts; fossil lists and excellent photographs facilitate correlation with other areas in the world; and associated igneous rocks are also described, and tables of chemical analyses are appended to each chapter. Special headings deal with facies variations, structural relations, age of deformation, paleogeography, metamorphism, and many other pertinent topics.

As in many other continents, the evolution of the great Paleozoic geosyncline of Australia ended with the Carboniferous period. Glacial beds of Permo-Carboniferous age are recorded in all seven states of Australia. Late in the Permian the great terrestrial basins of New South Wales, Queensland, and Western Australia were filled with sandstone, shale, and very extensive deposits of high-grade coal. To what extent these strata may also contain natural gas and petroleum is one of the most important problems of Australian fuel resources.

Thin continental deposits of Triassic and Jurassic age cover large portions of Australia and are the reservoirs of the extraordinarily large artesian basins of this continent. During the Cretaceous, however, marginal parts of Australia were once more flooded, and this period of unrest ended with the Marybury orogeny, comparable to the North American Laramide revolution. Henceforth the continent has stood above sea-level, essentially in its present form; and, from early Tertiary on, erosion surfaces have formed that are remarkable for the manner of preservation and the enormous size of the areas over which they have developed.

Volume 2 begins, therefore, with a most interesting account of the physiography of Australia, subdivided areally, and concludes with two chapters on the physiographic history and soils. The ancient erosion surfaces are represented, for the most part, by a pisolitic laterite, or duricrust, "really the B-horizon of a soil formed during a period of tropical climate on a peneplain surface" (vol. 2, p. 129). In a few places the overlying A-horizon is still preserved. One of the largest duricrust-laterite surfaces, in Queensland, extends over 4° of latitude, as a belt 250 miles wide. Fossil podsol is thought to survive on a large scale in southwesternmost Australia. It is derived from deep weathering, *in situ*, of granite, greenstone, paragneiss, and other crystalline rocks and forms patches, about 20 miles in diameter, "of almost incredibly monotonous levelness" (vol. 2, p. 129).

Most of the ancient erosion surfaces can be traced to the Miocene; some are even older. They have been able to survive in Australia because of a combination of climate and low continental relief. Nevertheless, in some districts, notably in Queensland and in southeastern Australia, there is evidence of considerable warping of the land surface during Tertiary time, and volcanic eruptions produced extensive flows, tuffs, and pyroclastics of varied composition. Associated with these volcanic rocks that extend from Torres Strait to the south end of Tasmania are alkaline plugs and lava flows. Owing to crustal warping in central Queensland, the Tertiary drainage of this part of the continent has been widely disarranged. The gentle rise of a low, meridionally trending tract of land, across the courses of westward-draining streams, caused "a profound change in the hydrography, since west-flowing rivers were beheaded and their headwaters ponded until channels were cut for them through gaps in the old divide, when they flowed to the east" (vol. 2, p. 124). The lacustrine deposits of eastern Australia are believed to record many similar changes of drainage, temporary basin-fill, and subsequent drainage in new directions, due either to faulting or to volcanism or to a combination of these with other factors.

The remainder of volume 2 is given over to economic geology. As Australian ore deposits have been described and discussed in many American and foreign journals, merely the

sequence and length of chapters will be listed here. An introductory "Distribution of Ores in Space and Time" of 10 pages outlines the location of the principal mining districts and ages of the mineralized rocks. Six maps show the various pre-Cambrian, Paleozoic, and later areas of deposition. Table 29, page 154, is a correlation chart showing the district names, list of principal metals, and geologic age. Question marks show where the age is doubtful. Individual chapters deal with gold (78 pp.); silver, lead, zinc, cadmium, iron, manganese, copper (47 pp.); tin, tantalum, molybdenum, tungsten, antimony, bismuth, titanium, zirconium, uranium, radium (40 pp.); and other metals (8 pp.). Nonmetallics, including gemstones and building stones, are given 58 pages; coal, 100; oil shale, petroleum, and natural gas, 23; and the closing chapters deal with artesian basins and ground water (80 pp.).

Appended to the series of stratigraphic chapters of volume 1 is a chapter of 23 pages on the geology of Australian New Guinea.

Each chapter in the book closes with a large list of references, in which the literature through 1946 is listed, and the two text volumes have comprehensive indexes of 27 and 23 pages, respectively.

The geological map of Australia is a large wall map of about 7 × 5 feet. The legend lists 56 formations, and along the margins are 13 cross sections, some showing particularly important local areas, others covering the entire continent. The map is dated 1931, but some later observations seem to have been added. However, the copy which the reviewer had before him seems to be a preliminary edition, and the final edition may contain more recent data. The Geological Sketch Map of Australian New Guinea includes the Bismarck Archipelago. Twelve formation groups have been distinguished on it, and one cross section in north-south shows the generalized structure of the island.

It is, of course, impossible to do justice to the wealth of information and highly stimulating discussion contained in the pages of this work. A brief review can mention but a few features that impressed one reader. The stratigrapher will find the volumes a treasure house of information on fossils, correlation, and paleogeography. The student of ore deposits or of ground-water problems will find the observations of our Australian colleagues of great interest, in that they illustrate types of mineral paragenesis, structural control, or movements of pore fluids that may not be so obvious elsewhere. The geomorphologist will undoubtedly profit from reading the remarkably complete record of the ancient Australian erosion surfaces; and every geologist will be indebted to the authors of this book for writing one of the most massive and comprehensive monographs on the geology of a continent of which, alas, most of us are far too ignorant.

R. BALK

University of Chicago

Principles of Petroleum Geology. By WILLIAM L. RUSSELL. New York: McGraw-Hill Book Co., Inc., 1951. Pp. 508. $7.00.

Geologists have often been accused of being buried in the history of the past and the rocks of the present, so that they have little inclination to bring their profession to the notice of the world at large. Nevertheless, in the petroleum business geologists have made themselves felt in a large and essential portion of the economy of the modern world. The petroleum industry is not the creation of the geologist in the same sense that the chemical industry is the creation of the chemist or the burgeoning nuclear atomic industry is the creation of the physicist. Nevertheless, the search for new oil and the production of oil already found are the bases upon which much of our mechanized culture rests in peace and war. These two activities are so permeated with geological concepts and so largely administered by men to whom these concepts are second nature that it is only when one steps outside the industry that one realizes the extent to which these conceptions are foreign to much of business and industry. However, one likes to believe that the habits of scientific investigation, controlled imagination, and independent action fostered by exploration and production activities have had at least some influence on the intellectual and social climate of our time.

Since petroleum geology employs some two-thirds of the geologists in the profession, it is perhaps surprising that more books have not been written treating the subject as a major branch of applied science which has contributed to, as well as drawn from, the store of knowledge accumulated by pure science. Russell's book attempts such a treatment, and by and large, succeeds remarkably well. The

pure scientist will be pleased by the thoroughness of the discussion of the basic data underlying the concepts in daily use in petroleum work, while the practical geologist will recognize with appreciation the description in chapter ii of the multifarious outside duties that a geologist in active practice is expected to perform. All classes of readers will be pleased with the abundant and well-chosen illustrations. Most of them have been taken from the publications of the A.A.P.G., S.E.G., A.I.M.E., and similar authoritative sources. Some are apparently original drawings made to illustrate some particular point. All are legibly reproduced.

A detailed catalogue of all the subjects covered in the 492 text pages of this book would be both wearisome and superfluous. However, it may not be amiss to outline a few of the larger divisions of the book and to comment on some of the more important.

After covering briefly some of the fringe fields upon which petroleum geology impinges, such as law, administration, mechanics, the author discusses at some length the chemistry of oil and its associated waters, as well as the physical properties of these fluids. From here the discussion goes on into more purely geological subjects. Geological representation is first discussed.

Then the author proceeds to the types of geologic structures most important in petroleum geology. The large variety of structures discussed should go far to correct the common oil-field assumption that all structures are anticlinal. If the chapter has a shortcoming, it is that the common low-dip anticlinal structures are not emphasized quite in proportion to their importance in oil finding. Here again the resistant question of definition of a geosyncline crops up. Russell designates the West Texas–New Mexico Permian Basin as a geosyncline. This will raise eyebrows among those who believe that geosynclines are narrow troughs associated with rising and active orogenic belts.

After a full but very clear discussion of porosity and permeability, together with methods of determination, Russell goes on to a discussion of the classification of traps. Here he proposes another classification of the much classified oil-field traps. Fortunately, this classification is refreshingly simple and does not propose any new terms to learn. It consists of three main classes: (1) purely structural traps; (2) partly structural, partly stratigraphic traps; and (3) purely stratigraphic traps.

This discussion of the types and causes of the subsurface pressures serves as a prelude to the treatment of the nebulous and controversial subject of the origin of oil. This difficult subject is well handled by an impartial review of the literature, which reflects the uncertainty of most geologists concerning this important subject. Not many geologists can quarrel with the author's conclusion that "few positive useful generalizations can be made about the source rocks of oil."

The next chapter treats a subject equally important and nearly as controversial, the migration and accumulation of oil and gas. After tracing the historical development of the anticlinal theory and its successes in oil exploration, the author is unable to reach a conclusion as to the mechanics of oil and gas accumulation. The manner of occurrence of oil and gas suggests accumulation by buoyancy, but the known buoyant forces available are insufficient to account for accumulation in this manner. In this unhappy state the matter rests.

The study of general considerations is concluded by a chapter on regional alteration in which the carbon ratio theory is gently treated.

Such geologic subjects as unconformities and depositional features are fully treated. The section on reefs is adequate, but the accompanying illustrations unaccountably omit a section of the highly asymmetric and elongated reefs of the Upper Permian, although talus slopes of the Capitan Reef are mentioned on page 280. The Capitan Reef is the generic type of these reefs as well as an extremely important oil reservoir It is unfortunate that on page 279 a great deal of Capitan oil in the "Winkler" and Hendrick pools is placed in the older San Andres dolomite.

Bars, channel sands, and other shore-line features are clearly explained. The matter of relationships of geologic boundaries is carefully handled. Time lines are extremely important in the determination of structure; hence a fuller treatment of the subject would have been justified.

Surface indications of petroleum are, of course, of academic and historical interest in the United States today but are fully treated for their scientific value and importance in foreign exploration.

Salt domes occupy an entire chapter, which procedure may be justified by their scientific interest as well as their economic importance.

The present reviewer is perhaps not qualified to comment upon the subject, but the treatment seems to be full and practical. The author seems to favor buoyancy as the main cause of the intrusion of the salt, but tectonic "trigger action" to initiate the movement is required. The relation of oil production to salt domes is briefly summarized.

The next several chapters are devoted to the various methods of well logging; lithologic, electrical, and radioactive. The chapter on radioactive well logging is especially valuable, since the author was for a long time associated with this work. Thus this chapter contains much information either original or unfamiliar even to one using radioactive logs a good deal. The following chapter on correlation impresses on the reader that the way to learn log correlation is by doing it. To this sage advice the reviewer can only add his Amen.

The next section of the book concerns the description and evaluation of the various geophysical methods of exploration, beginning with geochemistry. As would be expected in such a survey, seismic methods come off with the best score, whereas geochemistry brings up the rear. In connection with the chapter on geochemistry Russell makes some rather sharp observations on the strong tendency to hurry new developments into the stage of commercial exploitation before laying the foundation of purely scientific research. With these remarks the present reviewer is entirely in accord. It is perhaps significant that the important gravity, seismic, and electrical well-logging methods were all developed in Europe, although their chief application has been in the United States. The same situation seems to exist in other fields of science. Possibly in Europe there is somewhat less opportunity for immediately profitable application of new processes, or possibly the natural conservatism of an older culture tends to retard premature application of scientific principles.

Also in the section dealing with exploration methods is a summary of methods of locating stratigraphic traps. After observing that both geological and geophysical methods leave even more than the usual number of uncertainties in exploring for these traps, the author comes up with the very practical expedient of taking larger lease blocks and encouraging more wildcats through contributions.

Although more time is spent by geologists in developing known oil and gas fields than in any other activity, only one chapter is devoted to this work. Possibly this is because much of the work involves the application of principles already treated in other chapters or possibly because this development work borders upon and overlaps petroleum engineering work, which is better covered by treatises in that field.

The last few chapters of the book look to the future. In the chapter on the search for oil on the continental shelves, Russell accepts Pratt's estimate as to possible reserves, which may be optimistic. This is probably of little practical importance, as the quantity of oil to be found on these shelves is undoubtedly large. Although the search for this oil off the coast of the United States has practically ceased recently because of a title dispute between the state and federal governments, it will undoubtedly be resumed in the not too distant future. Important production from the continental shelves awaits the solution of political and mechanical difficulties rather than the resolution of geological problems.

In a chapter on exploration for oil and gas the author addresses himself to the thorny problem of estimating possible reserves in unexplored territory and evaluation of wildcat prospects. Although he states the problems involved very well, the reader is left with the impression that these are problems that books do little to solve.

The last chapter, on the future of petroleum geology, points out that the future of petrolum geology is essentially the future of the oil business. Using Soliday's well-known predictions, the author points out that the peak of oil production may come in the United States about 1960. Well before that time, search for stratigraphic traps will dominate oil exploration, so that the importance of the geologist will increase relative to the geophysicist. When we come to the final stage of dependence on secondary recovery and synthetic fuels, the geologist will be relatively little used. Development of foreign oil will, of course, be several stages behind our own, but this will depend on many political and economic factors. Prophecy is an interesting but dangerous art. As Russell points out, a prophet's hearers should include a liberal supply of salt in their diets.

JOHN M. HILLS

Midland, Texas

"Outstanding Aerial Photographs in North America." ("Am. Geol. Inst. Rept.," no. 5.) Washington, D.C.: National Research Council, 1951. Pp. 87; figs. 4. $1.00. Mimeographed.

The Education Committee of the American Geological Institute has compiled a very useful listing of sample aerial photographs illustrating various geomorphic and structural features. Within the limitations of photograph quality, the examples selected are of familiar areas, well documented and/or well shown by topographic maps. Teachers, especially, should find this an excellent guide in assembling representative collections of photographs for teaching purposes.

The report includes, in addition, sections on types of aerial photographs; agencies from which they may be obtained and typical prices; stereoscopic study, including types of stereoscopes and dealers; location of features on areial photographs; and a selected bibliography relating to various aspects of aerial photographs and photography.

JEAN G. SIMMONS

University of Chicago

Journal of Geological Education, vol. 1, no. 1, "Mineralogy Number" (April, 1951). Association of Geology Teachers. Pp. 50. $1.15 per copy; $2.00 per volume.

The Association of Geology Teachers was founded in the Midwest in 1938 to "foster unity and cooperation among the teachers of the earth-sciences, and to promote high standards of instruction in this field." To further this end, the association has initiated, under the editorship of William F. Read, the *Journal of Geological Education*, intended as an outlet for papers devoted to teaching techniques.

This first number is concerned with mineralogy and includes nine short papers, most of which describe mineralogy as it is taught at each author's particular school and indicate the reasoning behind the organization and emphasis of the courses. A few papers consider in general the problems of teaching mineralogy, and one is concerned with care of mineral specimens.

To persons interested in improving their teaching methods and to persons faced with the problem of setting up courses for the first time, this new journal may prove a valuable source of information. It should enable effective dissemination of suggestions for organization and presentation of material.

JEAN G. SIMMONS

University of Chicago

Guide to Geologic Literature. By RICHARD M. PEARL. New York: McGraw-Hill Book Co., Inc., 1951. Pp. xi+239. $3.75.

Mr. Pearl has prepared an exhaustive account of geologic literature: a general introduction, including a chapter on methods of searching the literature (Part I); a section on library facilities, including treatment of various systems of library classification and cataloguing, types of indexes, location of important libraries, photographic reproduction of material, and translation (Part II); and a section on kinds of geologic literature (Part III). This third part makes up the bulk of the book and contains the following chapters: "Index Guides and Bibliographies," "Abstracts," "Periodicals," "United States Government Documents," "Organization Bulletins," "State Bulletins," "County and City Bulletins," "Bulletins of Other Countries," "Books," "Newspapers," "Theses," "Un-published Manuscripts," and "Maps," all of which include data on where the various publications may be obtained.

Most geologists will be familiar with a large part of Pearl's material. There should be few, however, who can claim to be aware of all the sources of information mentioned in the book. Students, especially, knowing only the major bibliographies and periodicals, may find it helpful.

JEAN G. SIMMONS

University of Chicago

Structural Geology of North America. By A. J. EARDLEY. ("Geoscience Ser.") New York: Harper & Bros., 1951. Pp. xiv+624; figs. 343; pls. 16. $12.50.

According to the Preface, this book is addressed "especially to advanced undergraduates in geology . . . understandable to the student who has had basic courses in mineralogy, lithology, and structural geology." The book is planned for an "advanced course in regional or

structural geology." As it is the author's purpose to "describe the structural evolution of the North American continent in post-Proterozoic time," the large shield areas are not described.

The book deals with the North American continent from Alaska and the Canadian Arctic archipelago to the Panama Canal and Antillean region. Introductory chapters inform the reader on stratigraphic correlations, maps, and the author's use of terms. The continent is subdivided into the Greenland-Canadian shield, the central stable regions, orogenic belts, and coastal plains; and the structural evolution of North America is sketched through the succession of principal periods. The more important stages are portrayed in sixteen colored plates that show the evolution of tectonic elements, such as domes, arches, basins, facies areas, shelves, and orogenic belts.

The individual provinces are taken up in thirty-one chapters. A large portion of each is commonly devoted to an introductory general description, which is followed by more detailed discussion of individual parts and problems. On the whole, the treatment is adequate and well balanced, although in reading a book that covers such a vast array of topics and problems it is easy to disagree with an author on where data, illustrations, references, and interpretation should have been expanded or reduced. All illustrations are well reproduced and generally have adequate captions and explanations. The reviewer would like to have geographic orientations added to all cross sections. Such would facilitate their usefulness and save the reader time. The pages of this book are large ($11 \times 8\frac{1}{2}$ inches) and allow for some fairly large maps and diagrams.

The author has generally found the latest and most important references on each area, though in a few cases he appears to have relied too much on compilations rather than on the original papers. There are a number of typographical errors in the book, and a check is needed to clear text and illustrations from misspelled words that may confuse some readers. The reviewer was surprised that the Bibliography does not list Blackwelder's *United States of North America* (1912); Waters and Hedberg's *The North American Cordillera and the Caribbean Region* (1939); and *Geology of North America*, vol. 1, 643 pp., by many authors (1939). R. G. Moss's *Buried Pre-Cambrian Surface in the United States* (1936) could perhaps also have been included in the list of references.

The style of the book is a bit heavy. The discussion moves from item to item, and rarely does the reader reach a point that affords a penetrating view into the core of the problems of a complex region. This is no criticism of the author, who intended to assemble the pertinent facts that make up the geological picture of North America. Students and professional geologists alike are deeply indebted to Dr. Eardley for the care and impartiality with which he has done this. The amount of critical reading, evaluation of reconnaissance and detailed work, of drafting, reconstruction, and balancing information gathered from the literature is immense. This book is likely to stimulate greatly all future structural work in this continent.

R. Balk

University of Chicago

Soil Survey Manual. By Soil Survey Staff, Bureau of Plant Industry, Soils, and Agricultural Engineering. ("U.S. Dept. Agriculture Handbooks," no. 18.) Washington, D.C.: Government Printing Office, 1951. Pp. vii+503; figs. 60. $3.00.

This manual by Charles E. Kellogg and associates explains in detail the kinds of units that appear on soil maps prepared by the Division of Soil Survey and collaborating agencies and presents a complete terminology for the description of soils. This terminology is in large measure applicable to surficial deposits. Such terms as "boulder clay," "silty till," and "loam," for example, are used widely by geologists but are rarely defined and doubtless do not always convey the same meaning to all readers. The same situation has existed in soil science. Standardization of terminology is one of the primary objectives of this manual.

The geologist with a proprietary interest in "parent rock material" is likely to forget the other soil-forming factors and the strong agricultural bias of the soil scientist. "The classificational units are defined narrowly enough to be homogeneous genetically and to permit making such significant differential predictions [for agriculture] as available knowledge permits." These units are three-dimensional bodies and can be delineated on the map after a careful study of the landscape. A grouping of soils of interest to the geologist is the catena or "group of soils developed from one kind of parent material but differing in characteristics due to differences in

relief and drainage." Catena keys, included in many soil survey reports, are aids to the geological interpretation of soil maps.

Soil maps are prepared in great detail. The field data are commonly plotted on aerial photographs on scales of about 4 inches to the mile and published at approximately one-half reduction. Such maps serve many other purposes besides those that are strictly agricultural, such as for tax assessment and for highway engineering. "In fact, no other maps of large areas of land are made in such detail and involve so many significant factors as do soil maps." The statement is made that, "with interpretation," soil maps can be used as maps of surficial geology or of land forms or in studying geomorphological processes. The phrase "with interpretation" should be emphasized. The accuracy of such generalizations varies between wide limits. Some modern soil maps delineate stream terraces, for example, far more accurately than almost any geologic map. However, the map maker and the map interpreter are seldom fully acquainted with the facts, philosophy, and terminology used by one another.

The manual contains a wealth of data on how soils are described in terms of horizons, color, texture, structure, consistence, reaction, and internal drainage. Color determinations are made with a soil color chart that contains a part of the Munsell color chart. It has a wider range of colors, comparable to those of soil horizons, than the "Rock-Color Chart" that is distributed by the National Research Council (1948). The color names are those in use by soil scientists and do not entirely conform to those used on the "Rock-Color Chart." One chapter is devoted to estimating and mapping salts and alkali in the soil.

With the growing interest in "ancient" soils ("paleosols") as markers of possible stratigraphic significance or as relics of past climatic episodes, the geologist will find this manual useful as a guide to the terminology used by the soil scientist in describing such "ancient" soils, for many of the terms are new to the geologist and some of them (for example, "gravelly") have a geological meaning and connotation that differ from those in soil science. To a geologist the system of horizon nomenclature is exceedingly complex. In a simplified form, however, it has some advantages over the fivefold classification of Leighton and MacClintock (1930), especially when dealing with "buried" soils or profiles that contain horizons inherited from past climatic episodes.

The characteristics and use of aerial photographs in soil mapping are presented, together with good advice on the requirements of ground photographs for publication, especially photographs of soil profiles. "For scale, a 60-inch rule of unvarnished and unpainted wood with large black figures is satisfactory. The zero point of the ruler should always be exactly at the top of the A_1 horizon. Good scales make it possible to bring several pictures to a common scale by differential enlargement." A special bibliography of soil surveys is included, in which reports representative of contrasting soil regions or of various features of maps and reports are listed, together with a brief descriptive statement. Numerous sample descriptions of soil series and a guide to map scales are given in appendixes. In the Index, numbers in bold type indicate references to principal definitions or explanations.

C. S. DENNY

U.S. Geological Survey
Beltsville, Maryland

The Northampton Sand Ironstone: Stratigraphy, Structure, and Reserves. By S. E. HOLLINGWORTH and J. H. TAYLOR. ("Great Britain Geol. Survey Mem.") London: H.M. Stationery Office, 1951. Pp. 211; figs. 18; pls. 6. 17*s.* 6*d.*

This memoir is one of a new series being issued under the general title of "The Mesozoic Ironstones of England," in which the extent, characteristics, and economic possibilities of England's major deposits of iron are re-evaluated. It is a companion volume to *Petrology of the Northampton Sand Ironstone Formation*, by J. H. Taylor, which was published in 1949.

The Northampton Field, an area approximately 80 by 20 miles in extent, accounts for more than half of the total British production of iron ore. Worked intermittently since Roman times, the district entered major development in 1853, since which time it has yielded approximately 250 million tons, chiefly from shallow open pits. Present annual production is between 5 and 10 million tons, or about comparable to that of the Birmingham district of Alabama.

The Ironstone is at the base of the Middle Jurassic Inferior Oölite series. It is a relatively

flat-lying bed, 12–20 feet thick, the workable portion of which is generally 7–12 feet thick. "It is not a record of continuous deposition but of sedimentation interrupted by intervals of erosion, non-deposition and leaching, or other secondary changes." Where unweathered, the rock consists chiefly of oöliths of chamosite or limonite in a sideritic or calcitic matrix. Much of the mined ore has been enriched by preglacial oxidation. "In general the iron content of the workable stone ranges from 28–35 percent, silica from 6–18 percent and lime 2–10 percent." The depth of cover ranges from zero at the western and southern margins of the field to 100–200 feet at the eastern margin. In part the boundaries of the field are set by limits of outcrop, but to a greater extent the limitation is imposed by facies changes into sandy, unworkable material. The reserves total in excess of a billion tons of rock containing more than 25 per cent iron.

The chief structural features are of superficial origin, related to flowage of the underlying Lias clay toward the valleys. In the early stages of dissection, "bulges" of Lias clay develop in the valley bottoms; as the valleys deepen, outward flow of the clay causes a marked valleyward lowering of the overlying beds ("camber"), plus "dip-and-fault" structures, filled fissures ("gulls"), and "sags." The structures thus formed may have an amplitude on the order of 100 feet and are a major consideration in mining development.

It seems to this reviewer that at least a major part of the 1949 memoir on the petrology of the Ironstone could have been incorporated to great advantage in the present volume. Publication as separate memoirs has resulted in a considerable amount of duplication, as in the sections on lithologic succession and composition, and mutual loss. Most of the information and illustrations contained in the first memoir regarding mineralogy of the Ironstone, for example, are pertinent to the problems of extraction and beneficiation discussed in the second; on the other hand, the descriptions of lateral variations and the chemical analyses contained in the second volume are important to the problems of origin of the Ironstone discussed in the first.

Black-and-white maps at a scale of 2 miles to the inch show the generalized extent of the field, the depth of cover, and the locations of workings. The actual mapping was done at a scale of 6 inches to the mile; these maps are not published but have been made available for inspection.

H. L. JAMES

U.S. Geological Survey

Physical Geography. By ARTHUR N. STRAHLER. New York: John Wiley & Sons, Inc.; London: Chapman & Hall, Ltd., 1951. Pp. ix+442; figs. 514. $6.00.

This text is intended for a two-semester elementary course without prerequisites in geology, basic sciences, or mathematics and follows closely the tradition of Salisbury, Tarr, De Martonne, and others. It is lavishly illustrated and almost encyclopedic in coverage. Laboratory material is included at the end of each chapter, and colored slides and film strips integrated with the text are available from the publisher.

The contents are indicated by the titles of the three major subdivisions: Part 1, "The Earth as a Globe"; Part 2, "Maps and Landforms, Rocks and Structures"; and Part 3, "Weather and Climate, Natural Vegetation and Soils."

LELAND HORBERG

University of Chicago

ERRATUM

In "Change of Melting Point of Diopside with Pressure," by Hatten S. Yoder, Jr., vol. 60, no. 4, p. 367, the last equation in n. 2 should be:

$$\lambda = \left(\frac{\partial E}{\partial V}\right)_\theta = \theta\left(\frac{\partial P}{\partial \theta}\right)_V - P.$$

PUBLICATIONS RECEIVED

Additional Well Logs for North Dakota. Compiled by Wilson M. Laird, Marjorie Ness, and Clarence Klipfel. North Dakota Geol. Survey, Rept. Inv. 7. Grand Forks, 1952.

Bibliography of Seismology, Nos. 8, 9. Pub. Dominion Obs., Ottawa. Ottawa: Edmond Cloutier, 1951.

Ceramic and Refractory Clays of South Australia. By A. J. Gaskin and H. R. Samson. South Australia Geol. Survey Bull. 28. Adelaide, 1951.

Coal Resources of the Cretaceous System (Dakota Formation) in Central Kansas. By Walter H. Schoewe. Univ. Kansas Pub., State Geol. Survey Bull. 96, pt. 2. Lawrence, 1952.

The Concealed Coalfield of Yorkshire and Nottinghamshire. By W. Edwards. Dept. Sci. and Industrial Research. Geol. Survey of Great Britain. His Majesty's Stationery Office, 1951.

A Course in Instrumental Analysis. By Lewis G. Basset, John H. Harley, and Stephen E. Wilberley. Rensselaer Polytechnic Inst. Bull., Eng. and Sci. Ser. 66. Troy, N.Y., 1951.

La Formation du sédiment calcaire du Lac de Neuchâtel, étude chimico-physique. By Claude Portner. Travaux de l'Institut de Géologie, Université de Neuchâtel. Bale: Imprimerie E. Birkhaeuser & Cie S.A., 1951.

A Geological Reconnaissance Survey . . . Including Parts of the Yalgoo, Murchison, Peak Hill, and Gascoyne Goldfields. By W. Johnson. Western Australia Geol. Survey, Bull. 106. Perth, 1950.

Ground-Water Resources of Pawnee Valley, Kansas. By V. C. Fishel. Univ. Kansas Pub., State Geol. Survey Bull. 94. 1952.

List of the Principal Operators and Owners of Mines and Quarries in the Province of Quebec. Quebec Dept. of Mines. Quebec: Rédempti Paradis, 1951.

Magnetic Map of Rolette and Towner Counties. By N. N. Kohanowski. Scale: 1 inch = 2 miles. North Dakota Geol. Survey, Rept. Inv. 6. Grand Forks, 1952.

Metamorphism and Granitisation. By H. H. Read. Alex. L. du Toit Memorial Lectures, No. 2. Geol. Soc. South Africa, Annexure to Vol. 54. Johannesburg: Hortors Ltd., 1951.

The Mining Industry of the Province of Quebec in 1950. Quebec Dept. of Mines. Quebec: Rédempti Paradis, 1952.

Minor Elements in Kansas Salt. By Russell T. Runnels, Albert C. Reed, and John A. Schleicher. Univ. Kansas Pub., State Geol. Survey Bull. 96, pt. 4. Lawrence, 1952.

Moulding Sands. By K. R. Miles and H. A. Stephens. Mineral Resources of Western Australia. Western Australia Dept. of Mines Bull. 5. Perth, 1950.

A New Mastodont from the Miocene of Oregon, with Remarks on *Gomphotherium*. By Theodore Downs. Univ. California Pub. in Geol. Sci., vol. 29, no. 1. Berkeley and Los Angeles: Univ. of California Press, 1952.

Normetal Mine Area, Abitibi–West County. By Carl Tolman. Quebec Dept. of Mines, Geol. Rept. 34. Quebec: Rédempti Paradis, 1951.

Papers from the Geological Department, Glasgow University. Vol. 23 (Octavo Papers of 1947–1950). Glasgow: Jackson, Son & Co., 1951.

Pontgrave-Bergeronnes Area, Saguenay County. By E. W. Greig. Quebec Dept. of Mines, Geol. Rept. 32. Quebec: Rédempti Paradis, 1952.

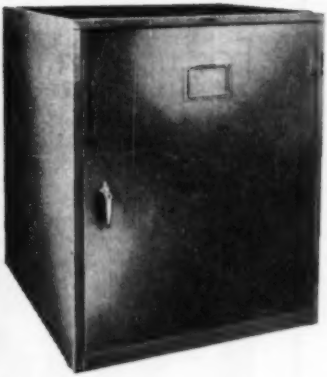
Report of the Committee on a Treatise on Marine Ecology and Paleoecology, 1950–1951. No. 11. Harry S. Ladd, Chairman National Research Council. 1951.

Report of the Geological Survey Board for the Year 1950. Dept. Sci. and Industrial Research. London: His Majesty's Stationery Office, 1951.

Sources of Lightweight Aggregates in Colorado. By Alfred L. Bush. Colorado Sci. Soc. Proc., vol. 15, no. 8. Denver, 1951.

Stratigraphy of North Dakota with Reference to Oil Possibilities. By Wilson M. Laird and Donald F. Towser. North Dakota Geol. Survey, Rept. Inv. 2. 1951.

No. 301LD with left hinged door.



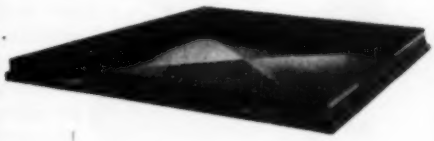
No. 301RD with right hinged door.

MODERN, ALL-STEEL

Lane STORAGE CABINETS For GEOLOGY SPECIMENS

A new, high standard in specimen storage

No. 301DD with removable drop door.



No. 301T Steel Tray

Capacity All Cases — 16 Trays

FOR ILLUSTRATED BROCHURE WRITE

Institutional Division

CHAS J Lane CORP

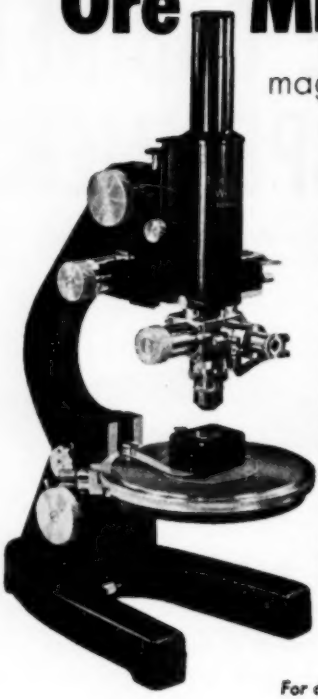
46 West Broadway, New York 7, N. Y.

For use with polarized,
reflected light... Leitz®

Polarizing

Ore Microscope MOP

magnification range 25 to 800 x



Designed for the examination of polished, opaque specimens in polarized reflected light, the Leitz Ore Microscope MOP meets the most exacting requirements of the mineralogist and geologist. The MOP eliminates lost motion, enables you to change *instantly* from transmitted to reflected light.

Increased light intensity and enhanced image quality are assured by the MOP's *coated* optical elements and lenses. Both the polarizer and analyzer are optical calcite crystals. The focusing stage accommodates all types of specimens, and the microscope stand will accept the Berek compensator, Leitz Universal Stages, and other accessories.

Ask your Leitz dealer to show you the Ore Microscope MOP. Compare it with other instruments of this type...see the difference in efficiency, quality and craftsmanship.

For details write Dept. JG

E. LEITZ, Inc., 304 Hudson Street, New York 13, N. Y.

LEITZ MICROSCOPES • SCIENTIFIC INSTRUMENTS • BINOCULARS
LEICA CAMERAS AND ACCESSORIES

ZEISS-WINKEL RADICALLY NEW STYLE

POLARIZING MICROSCOPE with INCLINED OBSERVATION TUBE

- Inclined observation tube with adjustable *Amici-Bertrand* lens, iris diaphragm extensible eye-piece sleeve.
- Dust-proof, integral tube analyser with degree scale, rotating about 180°, coated Telan lens system to establish telecentric pencil of rays and eliminate astigmatism.
- Filter polarizer and filter analyser of great light-transmission; neutral grey tint.
- Ball-bearing, rotating stage, graduated into 360° with vernier reading of 0.1°, with clamping screw, fine rotation adjustment and click-stop device to click-stop at 45°-intervals at any desired points.
- Low position, co-axial coarse and fine motions, controlled from either side.
- Objectives furnished in eccentric mounts for quick and accurate alignment.
- Equipped with integral illuminator permitting illumination by the Koehler principle.
- May be used with binocular head.

write for literature

C. A. BRINKMANN & CO.

P.O. BOX 532 GREAT NECK, N.Y.

BOOKS

BOUGHT and SOLD

We specialize in books on

GEOLOGY
PALEONTOLOGY
MINERALOGY

and related subjects

American and Foreign Publications

Inquiries and Offers Invited

THE BOOK HOME

Colorado Springs, Colo.

GEOLOGY APPLIED TO SELENOLOGY

By J. E. SPURR

"This is the first time that lunar features have been studied carefully by one trained and experienced in modern structural and igneous geology."—*Journal of Geology.*

Vols. I and II combined, FEATURES OF THE MOON, 1945, 430 pp., 95 text figures.....$5.00

Vol. III, LUNAR CATASTROPHIC HISTORY, 1948, 253 pp., 47 text figures.....$4.00

Vol. IV, THE SHRUNKEN MOON, 1949, 207 pp., 36 text figures $4.00

Complete Set.....$12.00

ROBERT A. SPURR

Box 413 College Park, Maryland

AVAILABLE PUBLICATIONS OF

The American Association of Petroleum Geologists

1947	**Comprehensive Index of the Publications of the A.A.P.G., 1917–1945.** Compiled by Daisy Winifred Heath. 603 pp. 6.75×9.50 inches. Cloth. **To members, $3.00**	4.00
1948	**Structure of Typical American Oil Fields.** Vol. III. McCoy Memorial Volume. 24 papers. 516 pp. 219 illus. Cloth. **To members, $3.50**	4.50
1948	**Appalachian Basin Ordovician Symposium.** From August, 1948, *Bulletin*. 264 pp. 72 illus. 6×9 inches. Cloth. **To members, $1.50**	2.00
1949	**Possible Future Oil Provinces of the United States and Canada.** 4th printing. From August, 1941, *Bulletin*. 154 pp., 83 figs. 6×9 inches. Paper. **To members, $1.00**	1.50
1949	**Problems of Petroleum Geology.** 2d printing. Originally published, 1934. 43 papers. 1,073 pp. 200 illus. 5.75×8.75 inches. Cloth. **To members, $4.00**	5.00
1950	**Structure of Typical American Oil Fields.** Vols. I and II. Symposium on Relation of Oil Accumulation to Structure. 3d printing. Originally published, 1929. Vol. I: 510 pp., 190 illus., 6×9 inches, cloth, $3.00. Vol. II: 750 pp., 235 illus., 6×9 inches, cloth, $4.00. Two volumes	7.00
1951	**Possible Future Petroleum Provinces of North America.** From February, 1951, *Bulletin*. 360 pp., 153 figs. 6×9 inches. Cloth. **To members, $2.50**	4.00
1951	**Contributions to the Study of Depositional Fabrics.** Rhythmically Deposited Triassic Limestones and Dolomites. By Bruno Sander (1936). Translated by Eleanora Bliss Knopf. 207 pp., 54 figs. 6×9 inches. Paper. **To members, $3.50**	4.00
1951	**Tectonic Map of the United States.** 4th printing. Originally published, 1944. Prepared under direction of National Research Council, Committee on Tectonics, Div. Geology and Geography. Scale, 1 inch = 40 miles. 7 colors. 2 sheets, each 40×50 inches. Folded, $2.00. In tube	2.50
1951	**Directory of Films and Slides of Possible Interest to Geologists** (2d ed.). Compiled under direction of Committee on Applications of Geology. 39 pp., 8.5×11 inches. Paper	0.50
1951	**Geology of California** (1933). By R. D. Reed. 355 pp., 58 figs., 26 tables. **Structural Evolution of Southern California** (1936). By R. D. Reed and J. S. Hollister. 157 pp., 57 figs., 14 photographs, 9-color tectonic map. Both offset reprinted. 5.5×8.5 inches. Clothbound together	6.00

Bulletin of The American Association of Petroleum Geologists. Official monthly publication. Each number, approximately 200 pages of articles, maps, discussions, reviews. Annual subscription, $15.00 (outside United States, $16.00). Descriptive price list of back numbers on request.

(Prices postpaid. Write for discount to colleges and public libraries.)

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

Box 979, Tulsa 1, Oklahoma, U.S.A.

"...the most compendious handbook of petrography ever issued..."

A DESCRIPTIVE PETROGRAPHY
OF THE IGNEOUS ROCKS

By Albert Johannsen

"An enormous amount of data, gathered from world-wide and often relatively inaccessible sources, is made available in one work. To petrographers it will be a mine of information and a great time-saver."—NATURE (England).

VOLUME I - Introduction, Textures, Classifications and Glossary . $5.00

VOLUME II - The Quartz-Bearing Rocks $8.00

VOLUME III - The Intermediate Rocks $6.00

VOLUME IV - The Feldspathoid Rocks and the Peridotites and Perknites $8.50

THE UNIVERSITY OF CHICAGO PRESS

SUBSCRIBE NOW TO THE EARTH SCIENCE DIGEST

The Earth Science Digest is an international illustrated magazine, issued monthly, devoted to the geological sciences. It contains articles and features of lasting interest to the professional and amateur geologist, mineralogist, and paleontologist. *Earth Science Abstracts* and the *New Books* column are now monthly features.

SUBSCRIPTION RATES:
1 year—$3.00; 2 years—$5.00
(Foreign: 1 year—$3.50; 2 years—$6.00)

Single copies—25¢ each. Vol. 5 began with the August 1950 issue. Special subscription rates (10 or more subscriptions: $2.00 each per year) allowed to educational institutions and societies.

THE EARTH SCIENCE DIGEST
JEROME M. EISENBERG, *Editor*
Box G-28, Revere, Massachusetts

A comprehensive survey of cosmochemistry and the chemistry of the geospheres.

GEOCHEMISTRY

By KALERVO RANKAMA
and TH. G. SAHAMA

This, the first modern account of geochemistry published in English and incorporating much of the extensive European literature, may well prove to be a classic.

The first section of the book treats the general aspects of geochemistry—chemistry of meteorites, abundance of elements and nuclides, geochemical structure and evolution of the Earth. Part II is devoted to a detailed discussion of the manner of occurrence of the elements.

900 pages. Bibliography. Indexes.
6¾×9½. 60 illustrations. $15.00

THE UNIVERSITY OF CHICAGO PRESS
5750 Ellis Avenue · Chicago 37, Illinois

ELIMINATE PERSONNEL ERROR and COST OF MAN AT BASE!

SURVEYING BAROGRAPH

MICRO

FOR ACCURATE FIELD SURVEYS AT LOWER COST

Readable to
ONE FOOT

The first reliable precision field MICRO Barograph made. Corrects the three main sources of error in Altimeter Surveys, namely, barometric change, air column temperature change and personnel error at base. Pays for itself in short time by eliminating cost of maintaining man at base.

This instrument can be used at any elevation from sea level to 10,000 feet. 24 hour chart shows pressure changes accurate to 0.001 in. merc. (equivalent to approximately ONE FOOT elevation) over a range of plus or minus 1.00 in. merc.

Instrument, complete with recording thermometer, charts and sturdy carrying case, weighs thirty-three pounds.

for best results use
AMERICAN PAULIN SYSTEM
Surveying Field Altimeters

Made Entirely in U. S. A.

MICRO **AMERICAN PAULIN SYSTEM** TERRA

1522 SOUTH FLOWER • LOS ANGELES 15, CALIFORNIA U.S.A.

Write Today for Literature

WORLD'S LEADING MANUFACTURER OF SURVEYING ALTIMETERS

Timely McGRAW-HILL Books

INVERTEBRATE FOSSILS

By Raymond C. Moore, C. G. Lalicker, and A. G. Fischer, University of Kansas. 766 pages, $12.00

A well-organized, comprehensive, descriptive guide to all important fossils, containing more than 400 line drawings, illustrating over 2,000 fossils, this text gives, first, clear accounts of important structural characters, especially of hard parts. It then discusses evolutionary trends. Stratigraphically arranged groups of representative examples are illustrated. Special emphasis is on *graphic presentation* and avoidance of *unnecessary terminology*.

INVERTEBRATE PALEONTOLOGY. New 2nd Edition

By Robert R. Shrock, Massachusetts Institute of Technology; and W. H. Twenhofel, University of Wisconsin. *McGraw-Hill Series in Geology*. Ready in September

One of the most complete and systematic treatments of invertebrate fossils yet published, this text discusses twenty-one phyla of invertebrates. A short chapter is devoted to conodonts. Considerable emphasis is placed on the morphology of soft parts, the architecture and structure of the hard parts, and the relations of the latter to the former. So organized that the student can use it throughout the several college levels of invertebrate paleontology.

PRINCIPLES OF PETROLEUM GEOLOGY

By William L. Russell, Texas A. and M. College. 501 pages, $7.00

An advanced petroleum geology text, this book provides a discussion of the principles, methods, and techniques important in petroleum geology. Emphasizing the practical applications of principles, the text covers the origin and accumulation of oil, important structures, classification of fields, stratigraphic features such as reefs, geophysics, and the various well-logging methods. Gamma ray and neutron well logs and electrical well logs are treated for the first time.

PETROLEUM GEOLOGY

By E. N. Tiratsoo. 449 pages, $7.50

This text covers both the academic questions related to the origin, migration, and accumulation of petroleum in the subsurface, and the practical problems of discovering and exploiting oil deposits. These include surface methods, such as geological mapping, aerial survey and the evaluation of oil seepages and asphalt deposits; and also subsurface methods of discovery, and the integration of physics and geochemistry with geology for this purpose.

Send for copies on approval

McGRAW-HILL BOOK COMPANY, Inc.

330 West 42nd Street New York 36, N.Y.

Prentice-Hall
COLLEGE TEXTS

Just Published!

ATLAS OF THE WORLD'S RESOURCES:

The Mineral Resources of the World

By WILLIAM VAN ROYEN and OLIVER BOWLES

—in collaboration with ELMER W. PEHRSON

Each of the twenty-nine basic minerals studied in this Atlas is examined from the viewpoint of Origin—Occurrence—Principal Producing Methods—Mining Methods or Methods of Extraction—Preparation—Reserves—Nationality of Control.

Because of their close collaboration with the Bureau of Mines, the authors are able to present an enormous amount of information never available before in map form.

In detail, and with a minimum of technical terms, they:

- interpret all data available on each mineral
- discuss the broad features of the world's mineral economy, considering . . .
  - —specific problems related to mineral exploitation
  - —geographic distribution of world production of minerals
  - —appraisal of the adequacy of certain major world mineral resources

Their discussions are directly related to the many problems arising today in geography, economics, political science, international relations, and military planning.

Double-checked for both accuracy and clarity by outstanding specialists, ATLAS OF THE WORLD'S RESOURCES shows exactly *how* and *why* leading mineral deposits are strategically important in our complex socio-economic structure.

180 pages, 15½" × 12½" August, 1952

Send for your copy today

PRENTICE-HALL INC. 70 FIFTH AVE-NY 11-NY